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Run-Off-Road Collision Avoidance Countermeasures Using IVHS Countermeasures

TASK *4-Volume 1*

Contracting Officer's Technical Representative's Precis

This report provides a basis for disseminating the preliminary contract results on a timely basis resulting in the information being available before the contract final reports are produced. Research performed during the remainder of the contract may support and/or modify the results, therefore, the material contained in this report should not be consider to be final. The current schedule calls for the completion of this research project by the third quarter of 1999.

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16 Abstract

The Run-Off-Road Collision Avoidance Using IVHS Countermeasures program is to address the single vehicle crash problem through application of technology to prevent and/or reduce the severity of these crashes.

This report describes the findings of the Task 4 effort. Task 4 focused on the development of preliminary performance specifications for run-off-road countermeasures. A total of 62 performance specifications were developed to ensure that potential run-off-road countermeasures meet the functional goals developed in Task 2. These performance specifications were divided into those that apply generally to run-off-road countermeasures, and those that apply specifically to lateral or longitudinal countermeasures.

These performance specifications were generated by developing and running a computer program called RORSIM to simulate the combined effects of the dynamical properties of the vehicle, the response of the driver, sensor measurements, environmental conditions and in-vehicle countermeasure systems.

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1.0 Executive Summary

This report presents a set of preliminary performance specifications for in-vehicle countermeasure systems to avoid single-vehicle-roadway departure (SVRD) or Run-Off-Road (ROR) crashes. These performance specifications were generated by developing and running a computer program to simulate the combined effects of the dynamical properties of a vehicle, the response of the driver, sensor measurements, environmental conditions, and an in-vehicle countermeasure system, This effort was supported by a contract (DTNH22-93-R-07023) from the National Highway Traffic Safety Administration (NHTSA). The project team for this contract included Carnegie Mellon University as the prime contractor, with subcontractor support from Battelle Memorial Institute, Calspan Corporation, and the University of Iowa.

The motivation for this program stems from the large number of ROR crashes. For example, there were approximately 1.21 million police-reported ROR crashes in 1992, according to the NASS/ GES (National Accident Sampling System/General Estimates System). These types of crashes represent approximately 20.1 percent of the total number of crashes, 26.8 percent of the injuries, and 4 1.5 percent of the fatalities in the GES data base for that year.

The overall scope of this contract for Phase I included four tasks, which spanned a period from September 1993 to September 1995. These tasks included (1) the establishment of ROR crash subtypes and causal factors, (2) development of functional goals related to the results of the first task, (3) operational assessment of existing hardware performance, and (4) development of preliminary performance specifications for in-vehicle countermeasure systems. These tasks were undertaken in a sequential manner, with the output of one task serving as input for the next.

There are several causal factors associated with ROR crashes, including driver inattention (12.7%), driver relinquishes steering control (20.1%), excessive vehicle speed (32-0%), loss of directional control (16-0%), evasive maneuver (15.7%) and vehicle failure (3.6%). The countermeasure concepts evaluated during this effort addressed the first three, and, to a limited extent, the fourth causal factors.

Driver inattention and driver relinquishing of steering control typically result in excessive lateral deviation from the vehicle’s normal trajectory. Two different technologies for detecting excessive lane deviations were tested in Task 3 and simulated in Task 4: forward-looking and downward-looking vision systems. In the case of the forward-looking system, a time-to-trajectory divergence algorithm is employed to compare the trajectory of the vehicle with the actual path of the roadway. If these two trajectories deviated by a predetermined amount within a given travel distance (i.e., within a preselected time-to-trajectory divergence) an alarm is issued to alert the driver. If the driver failed to respond to the alarm and the vehicle continued to departure the roadway, then the countermeasure may assume momentary steering control of the vehicle.

The downward-looking system measures the vehicle’s instantaneous lateral offset from the center of the road. Based on this offset, the vehicle velocity and the width of the road, an algorithm, called time-to-line crossing (TLC), calculates the time when one of the front tires would cross the lane boundary. When this time dropped below a preselected threshold, an in-vehicle warning is issued to the driver. If TLC drops even further without a response from the driver, automatic control can be initiated by the countermeasure.

According to the causal factor analysis efforts in Task 1, many roadway departure crashes occur when a vehicle attempts to negotiate a curve at too high a speed. The ability to detect excessive speed depdends on knowledge of a number of factors, including the vehicle's speed, the distance to the curve, the geometry of the curve, and the condition of the pavement. A model of the longitudinal countermeasure from Task 3, based on a digital map and a Global Positioning System (GPS) sensor, was used to assess the performance of excessive speed warning systems.

In order to evaluate the performance of these countermeasures, a sophisticated analytic tool, called RORSIM (Run-Off-Road SIMulation), was developed by the project team to model sequence of events that occur during roadway departure crashes. RORSIM includes all relevant system parameters, including the vehicle, the road, driver, environment, sensors, and in-vehicle countermeasures. RORSIM is based on a commercial vehicle modeling system called VDANL, which was originally developed for NHTSA by Systems Technology Inc. Capabilities have been added by the project team to model the performance' of proposed countermeasure systems, and simulate the driver's response.

The vehicle presently modeled in RORSIM, a Ford Taurus, was selected by NHTSA as a representative mid-sized sedan to be used in collision avoidance research. The Taurus is defined in RORSIM by a set of approximately 125 parameters, whose values represent all the physical properties of the vehicle, such as total mass, equivalent spring rates of the suspension, camber angles of the wheels, etc. A number of simulated maneuvers were executed with the vehicle model to verify its performance and to determine the capabilities of the vehicle and driver.

RORSIM currently models a two-lane road, with a shoulder and a run out area beyond the shoulder. The coefficient of friction and coefficient of rolling resistance can be independently set for each of the vehicle's tires. RORSIM provides a convenient mechanism for specifying the geometry of the roadway in terms of a straight segment, a spiral entry to a curve, a constant-radius curve, a spiral exit and finally a straight section. Crown and superelevation can also be specified.

A closed loop steering algorithm, supplied with VDANL, constituted the basic form of the driver model. The project team added features to model human tolerance of small errors, periods of inattention, and finite reaction times.

Most of the simulations in this project were based on a clear, sunny day. RORSIM contains provisions to model a slippery road surface and impaired visibility. Wet or icy conditions can be replicated by reducing the coefficient of friction on the road and shoulder. Impaired visibility can be modeled by adding noise to the vision sensor outputs. Models for the effects of reduced visibility on countermeasure performance were derived from the experiments conducted in Task 3.

RORSIM was used to analyze the performance of the two decision algorithms employed by the two lateral countermeasures during normal driving conditions. Warning thresholds were selected to avoid triggering false alarms or control intervention during ordinary driving. The critical part of the analysis was the identification of the driver's last chance to prevent a roadway departure and the criteria that would initiate an alarm in time for a corrective response from the driver. The final step in this preliminary analysis was to measure each system's ability to distinguish between normal and emergency situations. The result of this analysis was a selection of thresholds at which a system would warn a driver or intervene in steering. The analysis was undertaken for a variety of speeds and road segments of varying radius of curvature.

The potential effectiveness of the two proposed lateral countermeasure systems was estimated using RORSIM by comparing their performance to that of an existing countermeasure system for which performance data is available. The Sonic Nap Alert Pattern, on the Pennsylvania Turnpike, consists of a series of grooves cut into the shoulder just outside the lane boundary. If an inattentive driver drifts outside the lane, these grooves make a loud noise, thereby restoring the driver's vigilance. The relative effectiveness of the two proposed lateral countermeasures was compared to that of the grooves by applying each of the three countermeasures to a test suite of 24 potential run-off-road crash situations (i.e., 6 speed/curvature combinations, combined with 4 potential crash trajectories). The results of this preliminary study show that both electronic countermeasure algorithms can significantly reduce the vehicle's maximum lane violation during near roadway departure crashes relative to SNAP, which has already been shown to prevent up to 70 percent of run-off-road accidents.

The final countermeasure investigated was the longitudinal algorithm, whose purpose was to ensure that the vehicle is operating at a safe speed when entering a curve. Since longitudinal motion does not require as extensive a set of vehicle dynamical equations as the lateral studies, the longitudinal analysis began with the kinematic equations of motion. These equations represent the vehicle as a point mass, and are based on the acceleration, velocity, and distance traveled.

The sensitivity analysis revealed several important constraints on the performance of longitudinal countermeasures. The analysis indicated that an estimate of the distance to the upcoming curve with accuracy of better than 40 feet is necessary if the countermeasure is to provide an accurate and timely warning of excessive speed. This result implies that GPS may be adequate to warn the driver of the presence of a curve ahead, but differential GPS may be required if the countermeasure is to provide a warning of excessive speed. A second important insight provided by these analyses concerned friction, especially sudden changes in friction due to patches of ice. The analysis showed that errors in the estimate of available side friction of less than 0.15 can lead to a 10 percent error in the estimated safe speed for a curve. More research is necessary to determine how friction can be estimated quickly and accurately enough to support a curve speed warning system.

The results of the above analyses were used to generate preliminary performance specifications to address the functional goals for potential run-off-road countermeasure systems. In order to be as comprehensive as possible, the performance specifications were generalized to be technology independent whenever possible. Concrete values were provided for those performance specifications where the Task 4 analyses provided specific minimum performance criteria.

The performance specifications developed in Task 4 are preliminary. Experiments to further refine and validate these specifications will be conducted as part of Phases II and III of this program.

2.0 Introduction

2.1 Background

In support of the mission of the U.S. Department of Transportation's National Highway Transportation Safety. Administration DOT/NHTSA) to ensure the safety of U.S. highway systems, the team of Carnegie Mellon University (CMU), Battelle, the University of Iowa, and Calspan was awarded contract DTNH22-93-R-07023 "Run-Off-Road Collision Avoidance Using IVHS Countermeasures". The overall objective of this three-phase contract is to develop practical performance specifications for single vehicle roadway departure (SVRD), or Run-Off-Road (ROR) crash avoidance systems.

2.1.1 Motivation

The Run-Off-Road specification program is motivated by the large number of such crashes, which are the source of considerable fatalities, injuries, and property damage. For example, as reported in the General Estimates System (GES) and Fatal Accident Reporting System (FARS), in 1990 there were over 1.5 million police-reported (PR) single vehicle crashes with 16,438 associated fatalities. Single vehicle roadway departures represented approximately 24.2 percent of all PR crashes and 36.9 percent of all crash fatalities in 1990. Countermeasures systems potentially could reduce significantly the number of SVRD accidents by warning the driver and/or assuming partial or full control of the vehicle under conditions where such accidents may occur.

Single vehicle run-off-road crashes represent the most serious crash problem within the national crash population. Analysis of the 1992 NASS GES file, conducted as part of the Task 1, indicated that approximately 1.2 1 million police-reported crashes of this type occurred in the US in that year. This number represented approximately 20.1 percent of the crashes in the GES database. In addition, more than 520,000 vehicle occupants were injured in run-off-road crashes in 1992 and this level of injury represented approximately 26.8 percent of the injuries in the GES database. In a similar manner, the 14,031 fatalities sustained in run-off-road crashes (FARS data) represented approximately 41.5 percent of the 33,846 in-vehicle fatalities that occurred in 1992 in the U.S. Thus, in terms of injury frequency and severity, run-off-road crashes are an extremely serious problem.

There are several causal factors associated with Run-Off-Road crashes. Some of these factors include: driver inattention (12.7%), vehicle speed (32-0%), evasive maneuver (15.7%), and loss of directional control on road surface (16.0%). These are weighted percentages and include both straight and curved roads.

2.1.2 Overall Program Scone and Objectives

Phase I of the program was conducted over the period September 1993 to September 1995, with a scope of "Laying the Foundation". Phase 1 consisted of the following four tasks:

- Task 1: Establish Run-Off-Road crash subtypes and causal factors by thoroughly analyzing the crash problem

- Task 2: Establish functional goals of candidate countermeasures based on intervention opportunities and mechanisms

- Task 3: Obtain basic operational, performance, and functional data by performing hardware testing of existing technologies

- Task 4: Develop preliminary performance specifications based on critical factors and models of crash scenarios

2.1.3 Program Organization

The Phase I work flow is linear in nature in that the output of one task becomes an input to subsequent tasks. In Task 1, data analyses were conducted to determine the circumstances associated with run-off-road crashes and the reasons why these crashes occurred. Engineering evaluations were also completed to establish the dynamic states of involved vehicles and the sequence of events associated with the crashes. These results were carried forward to Task 2, where a taxonomy was developed to classify the run-off-road scenarios in terms of the relative length of time over which the road departure occurred. This information was used to develop practical functional goals for potential countermeasures. In Task 3, the functional goals developed in Task 2 were used to formulate complete run-off-road countermeasures. These countermeasures were built and tested in situations that were identified in Task 1 to be representative of roadway departure crashes. The task discussed in the present report, Task 4, built on the results of the previous tasks. Mathematical models of the crash scenarios and proposed countermeasure systems were developed. The results of simulations using the models served as a guide to developing preliminary performance specifications.

Subsequent phases of this program will continue the development sequence. For example, in Phase II the contract team will review state-of-the-art technology and design test-bed systems. The test-bed systems will be evaluated in Phase III. The results of the Phase IlI tests will be used to modify and expand the preliminary performance specifications from Task 4.

2.2 Task 4 Overview

The ultimate purpose of Task 4 was to generate a set of preliminary performance specifications for potential countermeasures to avoid Run-Off-Road crashes. This goal was achieved by developing a computer simulation program based on a dynamic model of the vehicle/driver/sensor/countermeasure system under a wide range of operating and environmental conditions. This computer program was utilized to evaluate three different countermeasure concepts by simulating a vehicle (a Ford Taurus) that encounters an incipient Run-Off-Road scenario while traveling along a roadway. Results of simulating these scenarios were analyzed to determine the conditions under which a candidate countermeasure algorithm was effective, as well as to identify countermeasure performance requirements.

2.2.1 Scope

Three in-vehicle countermeasure systems were modeled and evaluated using the computer simulation program. They are a downward-looking lane departure warning system, a forward-looking lane departure warning system and a map-based curve speed warning system. The first two candidate algorithms were designed to detect excessive lane deviation. The countermeasure triggers a warning and possibly assumes momentary steering control if the vehicle starts to depart the roadway. The third algorithm was developed to ensure safe curve entry speeds of a vehicle by comparing the actual speed, the distance to the curve, and the design speed for the curve. The countermeasure issues a warning and possibly automatically decelerates a vehicle traveling at an excessive speed.

2.2.2 Objectives

The primary objective of this task has been to develop preliminary performance specifications to achieve the functional goals for run-off-road collision countermeasure systems that were formulated as part of Task 2 of this project. The specifications were based on critical factors of crashes identified in previous tasks and models of crash scenarios developed in this task.

A secondary objective, in support of the primary objective, was to develop a computerized mathematical model for evaluating countermeasure systems, which NHTSA could run on desktop “486” computers. The computer program includes models for the vehicle, the driver, the roadway, countermeasure sytems, and other factors relevant to the crash situation.

The model and other analytical tools were used together to estimate the effectiveness that a run-off-road crash countermeasure system would have as a function of pertinent input variables.

The preliminary performance specifications are presented in Section 8 of the present report. The computerized model is summarized in Section 5 of this report and is described more fully in Volumes 2 and 3 of this report, the User’s Manual and source code listing, respectively. The analysis conducted with the models to support formulation of the performance specifications in presented in Sections 6 and 7 of this report.

2.2.3 General Approach

As part of Task 4, the project team developed a sophisticated computer simulation package called RORSIM (Run Off Road SIMulation program) to predict the dynamic response of the driver/vehicle/countermeasure system under a wide range of operating, roadway and environmental conditions. RORSIM is an extension of the commercial code VDANL (Vehicle Dynamic Analysis NonLinear), which is a vehicle model originally developed for NHTSA by Systems Technology, Inc. (STI).

A key feature of RORSIM is a menu system that enables the user to “point and click” to establish a simulation scenario. Results of the simulation runs can be viewed with VDANL utilities, exported to a spreadsheet format, or exported for display with a postprocessor. The postprocessor supplied with RORSIM depicts a plan view of the vehicle over a user-specified time period. A strobe-like illustration is created which shows the vehicles's position and attitude at fixed time intervals within the display period.

RORSIM was used to support all of the Phase I tasks, and particularly to support the development of preliminary performance specifications for a Run-Off-Road countermeasures system. RORSIM was designed to be a convenient and user-friendly analysis tool for use by NHTSA engineers and others involved in collision avoidance research.

Diverse driving situations were simulated with RORSM to:

- Determine the limits of vehicle performance
- Define normal driving
- Analyze typical crash trajectories
- Identify critical moments in the evolving crash scenario
- Determine the vehicle trajectory subsequent to invoking the countermeasure
- Estimate the potential effectiveness of countermeasure systems.

2.2.4 Relationship of Task 4 to Other Program Tasks

The results of Tasks l-3 form the basis for the mathematical models developed in Task 4. For example, Task 1 provided in depth clinical studies concerning the dynamical state(e.g., typical crash trajectory parameters) of vehicles involved in Run-Off-Road crash and also on the causal factors to be addressed by potential countermeasures. These parameters and causal factors helped to shape the mathematical formalism related to the performance of the vehicle, driver and the environment. Task 2 developed functional goals, which specified countermeasures intervention opportunities during the crash sequence. The results of the Task 3 effort provided insight into the capabilities of potential countermeasure algorithms whose performance is bounded by currently available ITS technology.

2.3 Organization of Task 4 Report

Section 2 provides additional insight into the objectives of Task 4. Discussed in Section 3 is an overview of potential Run-Off-Road countermeasures , while Section 4 reviews the analysis methodology to evaluate them. Section 5 treats modeling and includes modeling aspects of the driver, vehicle and the environment, as well as an overview of RORSlM and its verification. Results of the lateral and longitudinal countermeasure system evaluations are given in Sections 6 and 7, respectively. Performance specifications are presented in Section 8. The conclusions of Task 4 are in Section 9.

3.0 Overview of Run-off-Road Countermeasure Systems

As part of Task 1, the project team compiled and studied a group of run-off-road (ROR) crash case histories. Figure 3-1, which is based on data of Task 1, shows that the causes ROR crashes fall into six broad categories. The figure indicates the fraction of run-off-road due to each cause. The largest single category is vehicle speed, which accounts for 32 percent of ROR crashes. The longitudinal countermeasure systems were developed to address these cases. Two of the categories pertain to situations where the driver is not exercising steering control of the vehicle. Driver inattention (which lead to 13 percent of the crashes analyzed in Task 1) includes cases where the driver has been distracted by something inside or outside the vehicle that does pertain to the task at hand. Driver relinquishing of steering control (causing 20 percent of ROR crashes) typically due to a physical condition such as a seizure, heart attack, or chemical impairment. Taken together, inattention and relinquished steering control are 33 percent of ROR crashes. The lateral countermeasure systems were developed to address these cases.

As in the previous tasks, two of the original six run-off-road crash causal factors identified in Task 1 are not addressed in this effort. The first is crashes caused by evasive maneuvers in which the driver intentionally swerves to avoid striking an obstacle but runs off the road instead. As was indicated in previous reports, countermeasures for preventing this type of crash are currently being investigated in the NHTSA rear end collision countermeasures specifications program, being conducted by Frontier Engineering. The second crash type not addressed is those caused by vehicle failures. These crashes typically result from tire blowouts or loss of power steering due to engine failure. The Task 1 analysis conducted from this program indicates that crashes from these causes are relatively rare (less than 4 percent of the run-off-road crash population). In addition, countermeasures to prevent these crashes would require redesigning automotive components in a way that is beyond the scope of this program.

One part of Task 2 was to develop a set of functions a countermeasure system could have performed that might have prevented the crashes analyzed in Task 1. The Task 2 report presented a series of functional goals for run-off-road countermeasure systems, which are summarized in Table 3- 1.

Three specific run-off-road countermeasure systems were tested in Task 3, to assess their ability to achieve the functional goals developed as part of Task 2. In the present task (Task 4), the proposed systems were analyzed mathematically to formulate preliminary performance specifications. The modeling in Task 4 also supported the hardware development of the systems in Task 3. The systems modeled in Task 4 were patterned after the systems used in Task 3, but some of the implementation details were different.

The basic functions of these countermeasure systems are 1) to identify incipient run-off-road conditions, and 2) to provide a warning to the driver and possibly assume partial or complete control of the vehicle to execute an avoidance maneuver. The manner in which these functions are accomplished may vary, depending on the sensor types, algorithms, and warning or intervention criteria.,

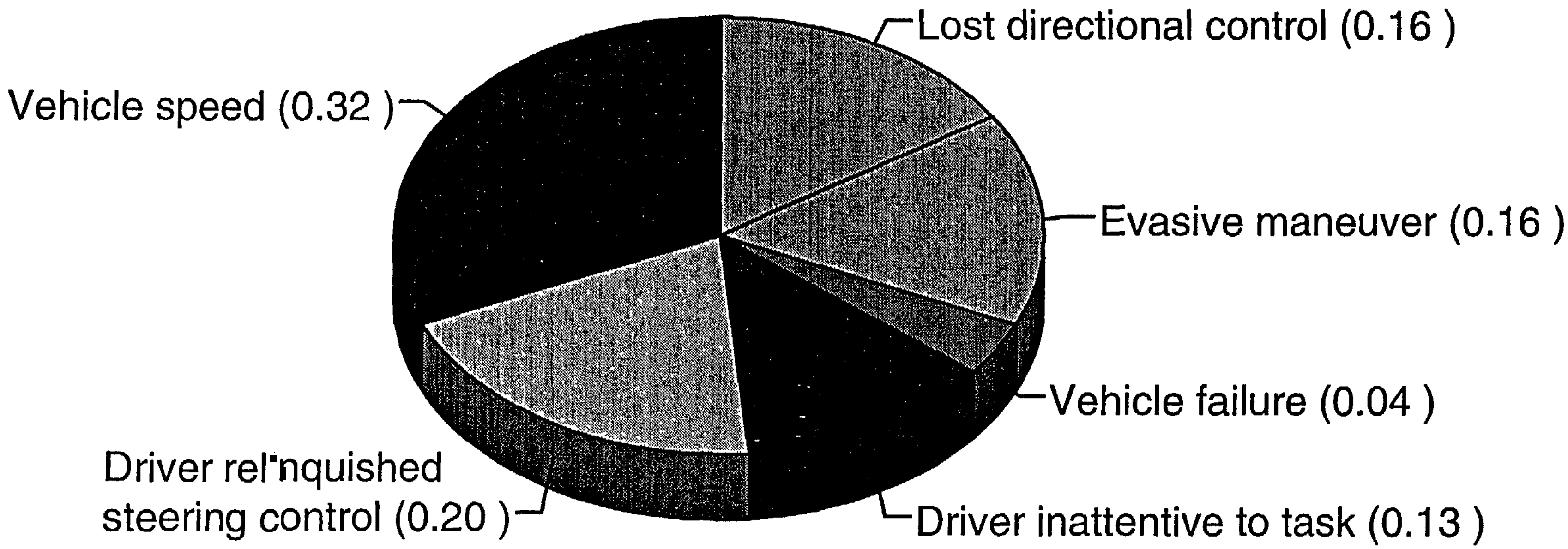


Figure 3-1 CAUSES OF RUN-OFF-ROAD CRASHES

Table 3-1
Functional Goals for a Run-Off-Road Countermeasure System

1. Monitor the Vehicle Dynamic Status
2. Determine Geometric Characteristics of the Upcoming Roadway Segment
3. Determine Vehicle Position and Orientation Relative to the Roadway
4. Determine Driver Intention
5. Detect Degraded Roadway Conditions
6. Process Data to Determine the Acceptable Speed for the Approaching Roadway Segment
7. Detect the Potential for Roadway Departure
8. Present a Phased Alarm to the Driver
9. Determine the Driver State
10. Modulate the Driver Control Input
11. Maintain or Regain a Safe Vehicle Attitude

3.1 Lateral (Steering) Countermeasure Systems

The lateral functional sequence of Task 2 was designed to detect when the vehicle begins to depart the road. It is intended to prevent those run-off-road crashes caused primarily by the driver's inattention and the driver's relinquishing steering control. Systems following this sequence use data about the dynamic state of the vehicle, in combination with information about the geometry of the road ahead, to determine whether the vehicle's current position and orientation are likely lead to a roadway departure. If the likelihood of departure exceeds a threshold, a sequence of driver interface functions is triggered to alert the driver of the danger and avoid a crash.

Two types of lateral systems were considered in this program as candidates for an effective countermeasure system. One has a vision sensor with forward preview to sense the vehicle's position with respect to the road at some distance ahead of the vehicle. In this project, the system used a decision algorithm called the Time-to-Trajectory-Divergence (TTD). To gauge the severity of the Run-Off-Road threat. This system will be referred to as the "forward-looking" system. The other lateral system has a vision sensor without preview; it looks down to sense the vehicle's current position within the lane. In this project, the system used a decision algorithm called the Time-to-Line-Crossing (TLC), This system will be referred to as the "downward-looking" system.

If the vehicle is bound for a roadway departure because the driver has been momentarily distracted from steering, a timely warning from the countermeasure system will probably be sufficient to restore the driver's vigilance. As suggested in the functional goals, the system may need to modulate the driver's control actions, perhaps by providing a momentary steering input. In severe cases, the countermeasure system may need to assume complete control of the vehicle. The current project focussed on the cases of warning and momentary intervention, for which technology is likely to be available sooner.

3.2 Longitudinal Position-Based (Curve Warning) Systems

In the longitudinal functional sequence of Task 3, the goal is to detect when the vehicle is traveling too fast for the upcoming roadway segment. It is designed to prevent those run-off-road crashes caused by excessive speed and lost directional control. Systems following this sequence use vehicle dynamic state and performance data in combination with information about the current pavement conditions and upcoming roadway geometry. They determine the maximum safe speed for the vehicle on the upcoming roadway segment. If the vehicle's current speed exceeds the safe speed, a sequence of driver interface functions is triggered to alert the driver of the danger and avoid a crash.

The work in Task 1 showed that the safety of highway traffic could be improved significantly if a countermeasure system could reduce the number of vehicles that are driving too fast through curves. Important findings were that 24.4 percent of SVRD crashes occur on curves and that 42.4 percent of fatal ROR crashes occur on curves [Carnegie Mellon University, 1994, Table 3-5]. Furthermore, speeding is the most frequent violation charged in ROR crashes (10.2 percent). Speeding and reckless driving charges total 14.3 percent of ROR crashes.

The ability to detect such a situation requires knowledge of the distance to a curve entry, the maximum safe speed for curve entry, and the current vehicle speed. A global positioning system (GPS) together with a digital map are candidate techniques for determining the upcoming roadway curvature and distance to the curve. Another candidate is a roadside transmitter that provides passing vehicles with information about the curve, possibly including real-time information about the pavement condition.

As with the lateral systems, the longitudinal countermeasure system might simply warn the driver in some cases or briefly apply the brakes in more urgent cases. Again, technical issues of detecting a completely incapacitated driver and safely stopping the vehicle were not addressed.

3.3 Critical Issues

There are several critical issues that influence the ability of a countermeasure system to operate effectively. These include:

- Environmental Effects: The weather can significantly affect the safe speed in both curved and straight roadways. The report includes extensive analysis and comments on this issue. The weather might also degrade the performance of the vision systems. This effect was studied in previous tasks, but it was only briefly considered during the modeling. All environmental effects will be important issues for further research.

- Measurement System Characteristics: The countermeasure system bases its decisions on information about the vehicle, the roadway, and the driver. Choosing sensors that can reliably provide the necessary information about the potential crash situation is essential to meeting some of the functional goals. Several different sensors were modeled in this project.

- Driver Characteristics: The drivers actions and inactions play some role in the majority of run-off-road crashes. The driver establishes the situation that the countermeasure system tries to correct. The countermeasure system will try in some way to influence the driver's actions, but the driver may heed or ignore a warning, and the driver may cooperate with or fight against (or sleep through) a control intervention. A considerable portion of both Tasks 3 and 4 included study of the driver's role in the avoidance maneuver.

- Vehicle Characteristics: The countermeasure system must base its decisions in part on the vehicle's ability to maneuver. This includes the handling characteristics, the propensity to roll over, and the braking ability. The computerized model of the countermeasure systems for this project incorporates a vehicle model that was originally developed and verified for NHTSA to study these issues.

- Roadway Characteristics: Another limiting factor in the ability of the driver to recover from an potential crash situation is the roadway. The width of the shoulder and proximity of obstacles determine the tolerable lane violation. The surface condition (whether slippery or dry) limits the ability of the driver to change the vehicle's velocity. These effects were explicitly included in the analysis.

- Improvement over existing systems: Even if a system is shown to perform as desired, it will not be deployed unless it is better in some sense than competing systems. Comparisons may be drawn in terms of cost, reliability of components, or other factors. An important part of the Task 4 work has been to estimate the effectiveness of the proposed systems in reducing the rate of ROR crashes. The potential effectiveness of the lateral systems was compared to that of shoulder rumble strips, which have already increased the safety of highway traffic.

4.0 Analysis Methodology

Vehicle behavior in potential Run-Off-Road (ROR) crashes was analyzed with two complementary methods. Digital simulation of specific situations and direct analysis of the relevant physics both provided valuable insight. In some cases, particularly those dependent on the subtle handling or steering characteristics of a vehicle (i.e., lateral vehicle control), the only way to answer questions is to simulate the vehicle, including its dynamic properties. In other cases, the physical principles are less complicated (i.e., longitudinal vehicle control), and much can be learned by directly analyzing the applicable equations. Sometimes, a combined approach was used where a simulation calculated how a certain quantity would vary through a maneuver. Then that information was the basis for a “spreadsheet” analysis. The ultimate effectiveness of systems in reducing the rate of ROR crashes was assessed, where possible, by comparing proposed systems to an existing system in a limited series of circumstances.

4.1 Simulation Modeling

Potential crash situations were simulated with a dynamic computer model developed by the project team named RORSIM (Run-Off-Road SlMulation). RORSIM includes all relevant components of the system: the vehicle, the road, the driver, and the countermeasure system. The vehicle model is a commercial package, VDANL, about which the rest of the model was constructed. The roadway and driver models were based on those supplied with VDANL, with enhancements to make them useful for countermeasure evaluation. RORSIM currently includes models of three separate countermeasure systems, which can be activated or inactivated independently. The countermeasure system models comprise an explicit sensor model, and a decisionmaking algorithm.

RORSIM was used in several ways:

- Find the limits of vehicle performance. The ability of a vehicle to recover from an emergency situation is bounded by, if nothing else, the limits of a vehicle to change its direction or speed. A few limiting cases were studied, and, to verify the model, some model results were compared with test track data from the Vehicle Research and Test Center.

- Establish “normal” driving characteristics. A collision avoidance system must not interfere with driving when a collision is not imminent. Many situations were simulated where the driver controlled the vehicle throughout the simulation, to learn how a proposed countermeasure system behaved with the vehicle not in danger of leaving its lane. As will be discussed in more detail later (see especially Section VI.2. l), “normal” is difficult to define when the controller is a human being.

- Project possible crash trajectories. RORSIM can simulate periods when the driver does not make steering corrections or does not heed warning signs to slow for a curve. It can project how the vehicle will approach and cross the edge of the road. Several simulations were allowed to proceed to a crash, so the output of sensors in such circumstances could be predicted.

- Identify critical moments in the evolving crash situation. A key issue in developing a countermeasure system is to identify when a driver must be warned (or when the system must take over) to prevent a roadway departure. Each of many different imminent-crash trajectories was simulated several times, with the driver resuming control at a different moment each time. Parameters in a countermeasure system could then be adjusted to warn the driver in time to respond in time to avoid a lane departure.

- Determine the vehicle trajectory after a countermeasure system has taken action. The action of a countermeasure system may be to warn a driver, who executes the corrective maneuver. A countermeasure system may go further and assume partial control of the vehicle. In either case, the ultimate success of the countermeasure system's action can be judged by whether the roadway departure was avoided or, if the vehicle departed its lane, how close it stayed to the lane. RORSIM can simulate the pre-event conditions, the onset of an emergency, the combined response of the countermeasure and the driver, and the corrective maneuver.

- Evaluate the effectiveness of a proposed countermeasure system. ROSIM can easily simulate several potential road-departure situations and record summary data--the maximum lane deviation of the front tires. By running vehicles "equipped" with different countermeasure systems through the same set of situations, the relative effectiveness of the countermeasure systems can be compared.

The vehicle in RORSlM can also be made to follow paths specified outside the model. For example, it can be driven along the same path as human subjects. Thus, the model can generate the output of a proposed sensor in the specified path, so it can be studied. An important use of the model has been to drive the vehicle through exactly the same path several times, with slightly different countermeasure system settings each time. The effect of changes in parameters such as sensor properties or warning thresholds could then be determined. The construction and use of the model is described fully in Volume II of this report, the RORSlM User's Guide.

4.2 Analytic Modeling

In some circumstances, the relevant equations are simple and have a small number of parameters. These cases permit the equations to be studied directly so more conclusive results can be obtained quickly.

Almost the entire analysis of the longitudinal systems (for preventing excessive speed in an approach to a curve) was done this way. The basic equations for a (point) mass on a banked curve and for a vehicle decelerating as it approaches a curve can both be solved in closed form. Over representative ranges of all parameters, the consequences of various inaccuracies were calculated. The resulting performance specifications could therefore be reasonably precise.

Portions of the lateral countermeasure analysis were also undertaken in an analytic method. For example, once the sensor output for a particular trajectory was calculated, the results of different decision-making algorithms could be calculated without repeating the simulation.

4.3 Effectiveness Estimation

One or both of the two modeling methods (i.e., digital simulation or direct mathematical analysis) can show whether a particular countermeasure system can prevent a crash in a specific scenario. The larger question, of course, is, "How effective is a proposed system in reducing the accident rate?" One way to answer that question using the available modeling tools is to simulate a representative suite of potential crash scenarios. The performance of a countermeasure system in the test suite can be compared against a standard.

The lateral counterrneasuee systems were tested in a suite of 24 cases with different speeds, road curvatures, and departure angles. The number of cases is too small to measure effectiveness definitively, but it is sufficient to demonstrate an analysis methodology and establish some trends. A more formal test suite would include a larger distribution of carefully selected conditions. A thorough test suite would also simulate accident situations taken from clinical samples, such as the cases examined in Task 1 of this program.

Success in preventing a roadway departure crash is a nebulous concept. Whether a crash occurs and, if so, the severity of the crash depends on many factors, especially the nature of roadside obstacles. (A wide, paved shoulder on a freeway is more forgiving than a utility pole on a low-volume rural highway.) Therefore, the measure of success used in this project was the distribution of maximum lane exceedances over the test suite. The philosophy is this: if one system warns a driver such that the right front tire is at most 1 ft outside the lane during the recovery, that may or may not lead to a crash, but it is better than another system where the tire is 2 ft outside the lane under the same circumstances.

The lateral countermeasure system standard selected for this report is the Sonic Nap Alert Pattern (SNAP), developed and deployed by the Pennsylvania Turnpike Commission [Wood 1994]. SNAP is a series of rumble strips that are cut into the shoulder, about three inches outside the driving lanes of the turnpike. If an inattentive driver drifts across the strip, a loud sound will get the driver's attention. The Turnpike Commission has limited, but quantitative, information on the reduction in the ROR crash rate on lengths of the turnpike where the system is in place.

SNAP can be simulated in RORSIM. A simulation vehicle, on a highway equipped with SNAP, executed the 24 potential crash scenarios in the test suite. The maximum lane exceedance of the offending front tire was measured in each case. The distribution of these exceedances was the standard of comparison for two proposed electronic systems, one with a forward-looking sensor and one with a downward-looking sensor.

The thresholds and other key parameters of the two proposed lateral countermeasure system algorithms (TTD and TLC) were selected through preliminary studies of simulation results. Then the "best" settings were used for the test suite to estimate the effectiveness. Section VI, Results of the Lateral Countermeasure Systems Study, presents this process in detail.

5.0 Modeling Approach

This section of the report discusses the various components of the model. The three countermeasure systems that have been implemented are presented, along with descriptions of the road, vehicle, and driver models. Important underlying assumptions and limitations of the analysis are declared. Finally, some exemplary results of the model are presented.

5.1 Analytical Method

Vehicle dynamics and the requirements of countermeasure systems were analyzed by a time-domain simulation, supplemented by direct analysis of the equations. The project team developed a package named RORSlM (Run-Off-Road SIMulation) to simulate a vehicle with a driver assisted by Run-Off-Road countermeasure systems.

RORSIM is an enhancement to VDANL (Vehicle Dynamic Analysis, Non-Linear), which is a general-purpose rubber-tired vehicle simulation program developed for NHTSA by Systems Technology, Inc. in Hawthorne, California [Allen et al 1992]. VDANL provides the basic vehicle dynamics model for the simulation as well as the closed-loop driver model. VDANL includes a 17-degree-of-freedom model of a general vehicle. The nonlinear differential equations of motion are integrated numerically by VDANL. The project team has written enhancements to VDANL for use in evaluating Run-Off-Road countermeasure systems. Capabilities have been added to simulate some of the driver's actions (and inactions), model the performance of various proposed countermeasure systems, and provide representative roadways.

The model is deterministic in the sense that almost every parameter, including the moment when the driver becomes inattentive, is fixed before a simulation begins. The only place where pseudo random numbers are used is where noise is added to sensor outputs. When closely related but distinct scenarios were to be simulated, different parameters were explicitly chosen before the analysis. This deterministic approach enabled simulating both the performance of perfect systems working with pristine sensor outputs, and the performance of the system under the worst possible conditions, such as when the sensor dropout occurs just as the vehicle is about to encounter difficulties.

The RORSIM package can simulate a complete scenario: a situation develops, it is sensed by the countermeasure system, the driver responds to the warning and regains safe control of the vehicle. When applied like this, RORSlM is useful for demonstrating that a countermeasure system can successfully prevent a Run-Off-Road crash under the particular circumstances modeled. Another use of RORSIM is to calculate the vehicle trajectory and the time histories of state variables. The key variables can then be exported to, for example, a spreadsheet for detailed analysis. This approach was useful for directly studying the effects of certain parameters without the computational price of an entire simulation for every case. A third type of analysis in this project did not use RORSlM at all. There were questions that could be answered without reference to nonlinear vehicle dynamics. Where possible, the applicable equations were analyzed directly.

5.2 Assumptions and Limit&ions

The analysis conducted to date has focused on demonstrating the capabilities of RORSIM and identifying preliminary quantitative performance specifications. The study of actual roadway departure crashes in Task I of this project [Calspan, 1994] showed that these crashes occur in myriad situations for diverse reasons. We do not claim to have studied all possible driver reactions in all potential crash situations. As was done for previous tasks, we eliminated from our investigation Run-Off-Road crashes caused by evasive maneuvers (15.7 percent of Run-Off-Road crashes). Instead we have focused our efforts on roadway departure crashes where human error was the primary cause. These include crashes caused by driver inattention (12.7 percent), driver relinquishes steering control (20.1 percent) and excessive vehicle speed (32.0 percent). In these crashes, the primary goal of a countermeasure is to detect the imminent danger and restore the driver's vigilance.

Perhaps the most significant limitation of RORSIM in its current form is the driver model. The driver is based on the closed-loop driver model supplied with VDANL. The model was originally developed more for the purpose of steering the modeled vehicle to follow a prescribed path than to mimic the behavior of a human being. As discussed in Section 5.5, the driver model has been enhanced somewhat too more closely resemble human response. Reaction times can be adjusted to model persons of different age or blood alcohol content. Unfortunately, good data on key aspects of performance, for example, drivers' practice of cutting curves, are not available. Therefore, even the vehicle trajectories presented for "normal" driving cases were arbitrarily chosen. We are confident that they represent valid, plausibIe conditions, but exactly how they relate to the driving population as a whole is difficult to say. The data from the simulator study conducted for Task 3 of this program [Tijerina et al 1995] should provide valuable data on the variety of normal driving practices.

The driver's reaction time is a function of the driver's position in the assumed population (e.g., 20-percentile young, healthy male), the driver's current condition (e.g., alert, drowsy, or drunk), and the alarm modality (e.g., a driver may react faster to a shaking handwheel than to a low-intensity light). These separate effects are not modeled explicitly; a single, fixed steering reaction time and a single, fixed braking reaction time account for whatever combined effects may influence them. Furthermore, when the driver resumes control of the vehicle, it is with the same "settings" as the driver had before the event. The model does not provide for a startled or scared driver. Of course, any of the limitations could be overcome through extensions to the model or further research. However, the results of the analysis in this report should be interpreted in light of these assumptions.

5.3 Countermeasure Systems Models

Three countermeasure systems were explicitly modeled in RORSIM. They are the same three that were investigated with in-vehicle and driving simulator tests as part of Task 3 of this program. There are two lateral countermeasure systems and one longitudinal countermeasure system. The two lateral countermeasure systems are designed to model a downward looking and a forward looking lane departure warning system, as identified and tested in Task 3. The longitudinal countermeasure system is designed to model an excessive speed warning system, as identified and tested in Task 3. Other, related countermeasure systems can be modeled by adjusting the parameters of the above three. Most notably, the Sonic Nap Alert Pattern (SNAP) [Wood 1994], which was developed by the Pennsylvania Turnpike Commission, can be simulated using a modified version of the downward looking case departure countermeasure model.

As suggested by the functional goals, all countermeasure systems have three basic components: (1) one or more sensors, (2) a decision making algorithm, and (3) an interface to the driver or vehicle. The sensor of each countermeasure system is modeled explicitly in RORSIM. The program calculates what the output of the sensor would be, given the current dynamic state of the vehicle, the characteristics of the environment, and the properties of the sensor itself, The sensor outputs in RORSIM are potentially subject to five kinds of degradation: bias error, random error, finite update rate, processing delay, output quantization, and dropout. The definitions of the degradations are in Volume II, the User's Manual. The output of the sensor is then processed by a separate decision-making module, which performs whatever calculations or logics are specified by the system. The decision-making module models the exact algorithm that would be included in an actual countermeasure system. The module may decide to do nothing, it may alert the driver to a potentially dangerous situation, or it may assume partial or complete control of the vehicle. Different types of warning interfaces (visual, aural, haptic and their variations) are not explicitly modeled in RORSIM. However, the driver's reaction time can be adjusted according to whether a certain alarm modality elicits a faster response. Active intervention is modeled explicitly for the longitudinal countermeasure system in the form of a brake pedal force dictated by the system that is applied to the brake pedal. Active intervention for the lateral countermeasure is modeled as steering input applied by the countermeasure. The control model used for this active steering intervention is the same one utilized to model the driver's steering response. Note that the interactions between the countermeasure's steering input and the driver's steering input are not modeled in RORSIM. In particular, the dynamics of a motor on the steering column, and the effects of a human either cooperating with or fighting against the systems steering input, are not included the current RORSIM model. The model could potentially be expanded to include these interactions in subsequent phases of the program.

This section presents the motivation and theory of each of the three systems.

5.3.1 Forward-Looking Lateral System Using Time to Traiectorv Divergence (TTD)

The first lateral countermeasure system uses a forward-looking vision sensor and a decision-making algorithm called Time to Trajectory (TTD). The basic principle of this system is that it notes the road position at some fixed distance ahead of the vehicle, calculates a trajectory to steer the vehicle to that position, and determines whether the driver's actual trajectory deviates significantly from the system's desired trajectory.

The geometry of the TTD algorithm is shown in Figure 5- 1. The road has some arbitrary curvature ahead of the vehicle, and the vehicle may be offset and rotated from the lane centerline. The sensor, as implemented in RORSIM, looks some fixed distance ahead of the vehicle. The distance is selected by the operator before the simulation. The sensor measures the perpendicular distance from the vehicle's longitudinal axis to the lane center point. This offset distance is labeled

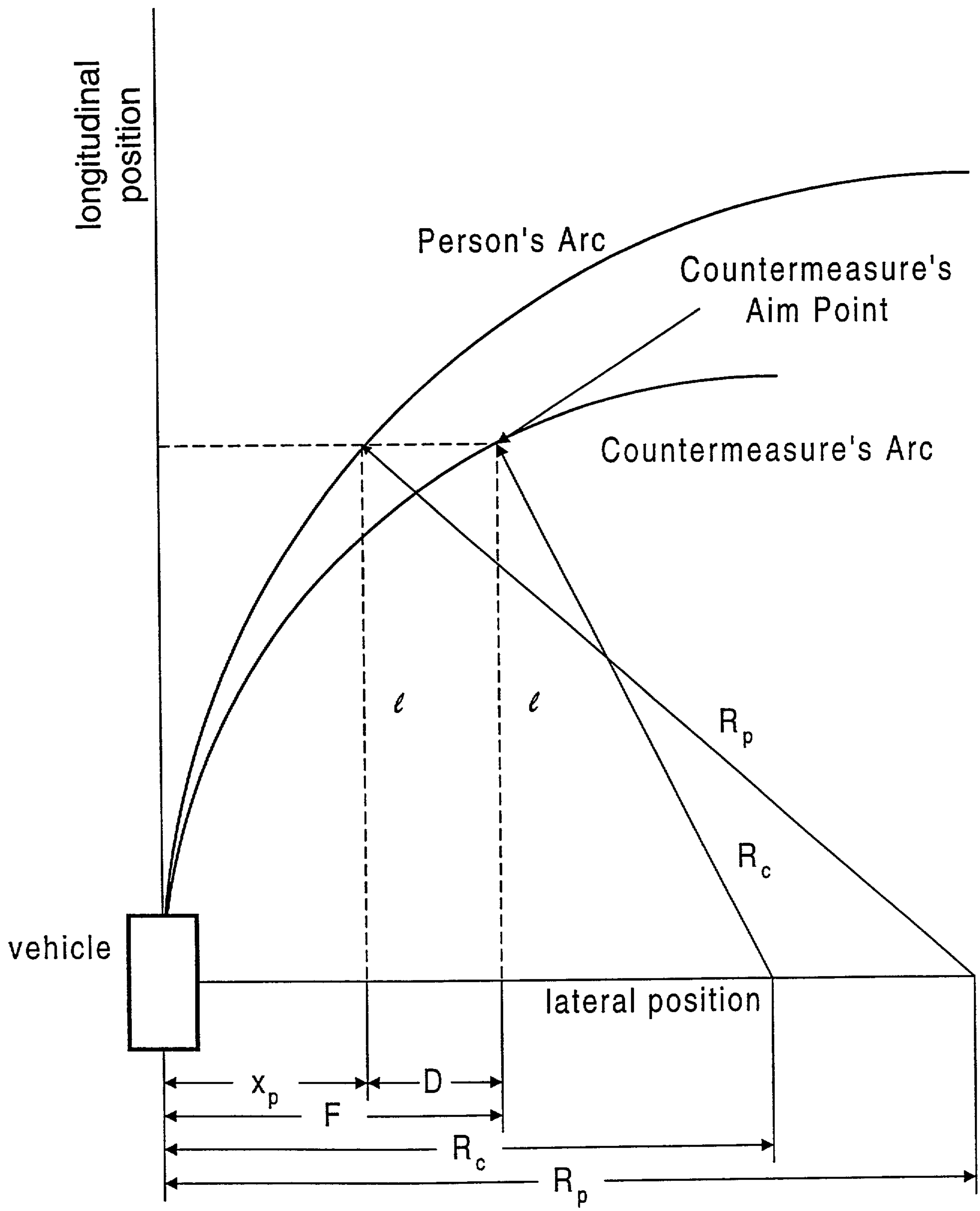


Figure 5-1 **GEOMETRY FOR CALCULATING TIME-TO-TRAJECTORY-DIVERGENCE (TTD). THE LOOK-AHEAD DISTANCE IS *l*. THE SENSOR MEASURES F, THE OFFSET TO THE ROAD CENTER AT THE LOOK-AHEAD DISTANCE**

F in the figure. The processing algorithm calculates the "optimum" path to drive the vehicle through the lane center point identified by the sensor. That is, it calculates the radius of the arc, R_c, which is tangent to the vehicle's longitudinal axis and passes through the aim point. The radius of the countermeasure's desired arc is approximated by

$$R_c \approx \frac{\ell^2}{2F} \qquad \textbf{5-1}$$

The system also measures the radius R_p of the curve currently being followed by the driver. (In RORSIM, the actual radius is computed from noiseless yaw rate and speed sensors.)

The system then projects the time that will be required for the actual arc to diverge from the "optimum" arc by a predetermined distance D. This time is the "Time to Trajectory Divergence" or TTD. The formula for TTD is

$$\text{TTD} = \sqrt{\frac{\dfrac{2D}{\left|\dfrac{1}{R_c} - \dfrac{1}{R_p}\right|}}{V}} \qquad \text{5-2}$$

Note that the TTD value represents the time it would take along the vehicle's current trajectory to diverge from the optimal path and as a result, TTD does not fall at a rate of one second per second as the vehicle approaches the lane edge. When the actual path of the vehicle is significantly different from the desired path through the target point, TTD will become very low. If the TTD value falls below a certain threshold, the system warns the driver.

53.2 Downward-Looking Lateral Svstem Using Time to Line Crossing (TLC)

The other lateral countermeasure system considered uses a downward- or sideways-looking vision system and a decision-making algorithm called Time to Line Crossing (TLC). In brief, the system continuously measures the distance to the edge line of the vehicle's lane and projects how soon the vehicle will cross the line, assuming it continues its current curvature.

In RORSIM the sensor for the TLC system measures the distance from the vehicle's right front tire to the right edge of the lane. The distance from the left front tire to the left edge is calculated from the front track width of the vehicle and an assumed lane width.

The algorithm for calculating TLC is depicted in Figure 5-2. The arc in the figure is the tire's projected trajectory, if its current radius of curvature remains constant. The time before the tire

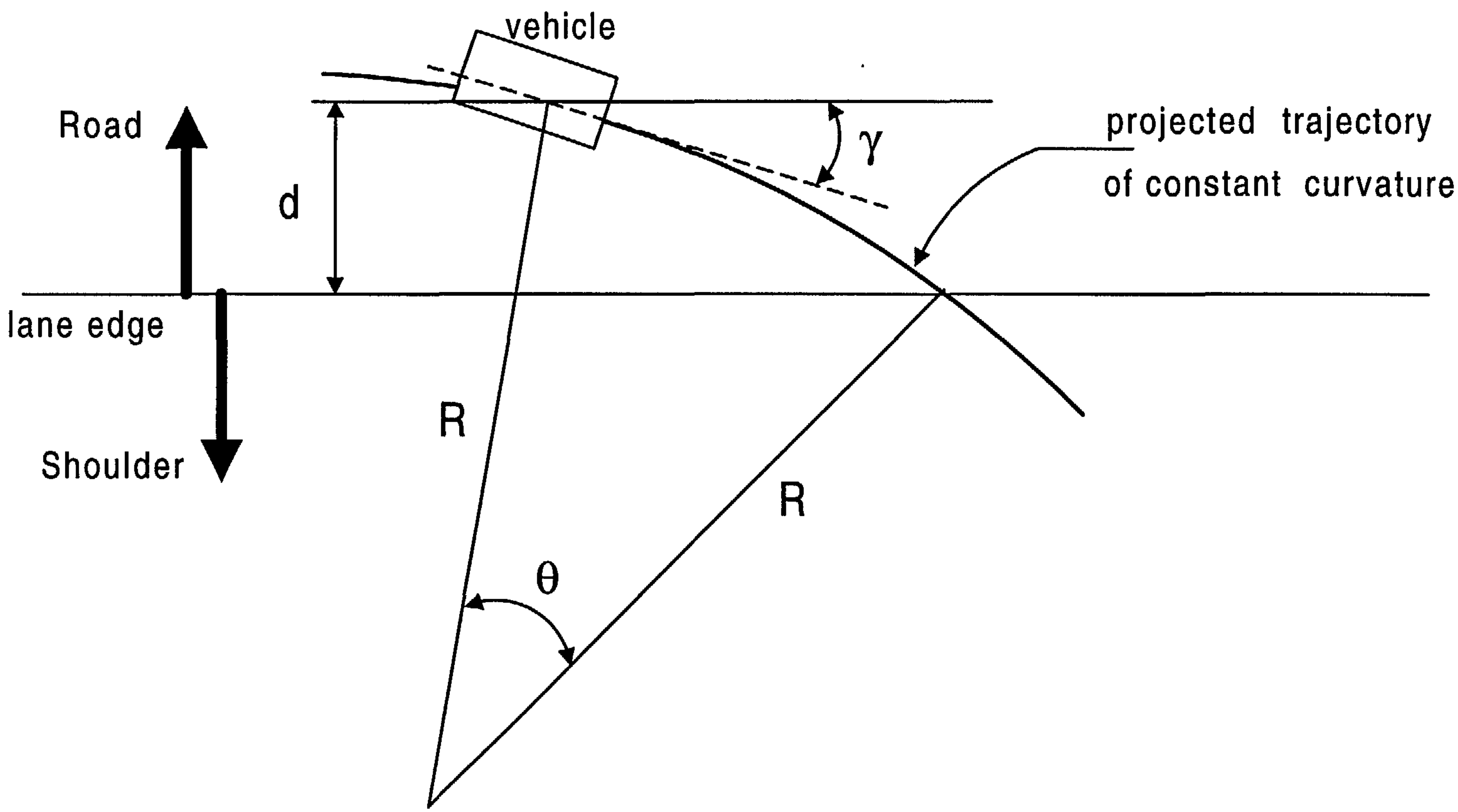


Figure 5-2 GEOMETRY FOR CALCULATING TIME-TO-LINE-CROSSING (TLC)

crosses the line is the ratio of the arc length to the speed along the arc:

$$\mathrm{TLC} = R\,\theta / V \qquad (5\text{-}3)$$

where

R = the current radius f curvature
θ = the angle swept by the radius before departure
V = the longitudinal speed of the vehicle.

The only geometric measurement is the distance d between the tire and the line. From this measurement (and its first two derivatives), the length of the arc can be calculated.

$$\theta = \cos^{-1}\left(\cos\gamma - \frac{d}{R}\right) - \gamma \qquad \gamma = \frac{\dot{d}}{V} \qquad R = \frac{V}{\dot{\gamma}} \qquad (5\text{-}4)$$

The algorithm within RORSIM has more cases to account for the fact that the vehicle may depart the lane to the left or right and its current curvature may be toward or away from the approached edge. As calculated in RORSIM, the TLC is a positive quantity if the vehicle's projected path will take it off the right side of the lane and a negative quantity if the path will exit to the left. Of course, the absolute value of TLC is used for threshold comparisons.

The TLC concept is the time that will elapse before the tire crosses an imaginary line at the side of the road. Usually, this line is the edge of the lane, but it could be inside or outside the lane edge. Some highways have rumble strips on the shoulder to alert drifting drivers. These strips can be modeled with the TLC system by placing the imaginary line just outside the lane, and setting the warning threshold to zero seconds.

5.3.3 Longitudinal or Curve Warning

The forward- and downward-looking countermeasures are both lateral systems (i.e., they assist the driver with steering). The curve warning system, on the other hand, is a longitudinal system. It helps the driver slow down to negotiate tight curves. This system notes that a curve lies ahead, measures the vehicle's distance to the curve, and calculates whether the vehicle can safely slow down before entering the curve.

In the team's embodiment of this system in Task 3, the countermeasure system determines the vehicle's position using a Global Positioning System (GPS) receiver. It consults a digital map to determine whether a curve is ahead and, if so, the geometry of the curve. Other implementations might use a forward-looking vision system to identify and measure the curve. Or, perhaps a roadside transmitter could give passing vehicles a message something like, "Caution! A curve is 300 ft ahead, and today's safe speed is 45 mph."

After the system has determined that a vehicle is approaching a curve, it compares the vehicle's current speed to its estimate of the maximum safe speed for the curve. It calculates the

required deceleration according to the kinematic formula,

$$a = \frac{V_o^2 - V_c^2}{2d} \qquad 5\text{-}5$$

where

V_o = the vehicle's current speed
V_c = the safe speed for the curve
d = the distance to the curve entry.

When the required deceleration reaches a predetermined threshold, the system warns the driver to slow down. In RORSIM, the curve warning system itself will apply the brakes to slow the vehicle if the required deceleration reaches a second threshold.

5.4 Vehicle Model

The vehicle modeled in RORSIM is a Ford Taurus and was selected by NHTSA as a representative mid-size sedan to be used in collision avoidance research by contractors and by NHTSA itself. A specific vehicle (e.g., a Ford Taurus) is defined in VDANL by a set of approximately 125 parameters. These values represent all the physical properties of the vehicle: the total mass, the equivalent spring rates of the suspension, the camber angles of the wheels, and many others. A complete parameter set for a 1995 Ford Taurus, based on measurements at the Vehicle Research and Test Center, was supplied to the project team by NHTSA [Chrstos, 1995]. Selected important properties of the vehicle are listed in Table 5-1. VDANL simulations using these parameters have shown general agreement with data from test track maneuvers.

VDANL was designed to be able to model most any tired vehicles, including tractors with semitrailers, by using appropriate values for the several parameters that define the dynamics of the vehicle. For this project, however, the Taurus parameters were used exclusively so the results of the study, where they are specific to a particular vehicle's performance capability, apply to a Taurus-like vehicle. Some of the results are based on purely kinematic analysis and, therefore, apply to all vehicles.

Table 5-l
Selected Properties of the Ford Taurus Model Used in This Study

Total Mass	105.75	$lb\text{-}s^2/ft$
Sprung Mass	93.58	$lb\text{-}s^2/ft$
Front Trackwidth	5.125	ft
Wheel Base	8.83	ft
Distance from rear axle to center of gravity	5.82	ft
Height of the center of gravity above ground	1.94	ft

5.5 Driver Model

The basic form of the driver model is the closed-loop steering control model supplied with VDANL. Although this model was originally developed to make a vehicle follow a prescribed course rather than to mimic human behavior, it was successfully enhanced to be suitable for a preliminary analysis of proposed countermeasure systems. The project team added features to model a human's tolerance of small errors, periods of inattention, finite reaction times. A simple speed controller was built so the actions of a human or a countermeasure system could be modeled.

Figure 5-3 is a block diagram of the closed-loop steering controller supplied with VDANL, with the RORSIM enhancements shown. The handwheel is rotated in response to errors in either the heading or the lane position of the vehicle. The system can follow curves in the road, and permits command to drive off the center of a lane (for example, when cutting a curve), The block labeled, "neuromuscular dynamics," is simply a second-order, low-pass filter to account for a human's limited ability to move quickly.

As supplied with VDANL, this controller follows a reasonable road path almost exactly. A human, on the other hand, meanders or rambles somewhat because of a tolerance of small errors. As in the example of Carson and Wierwillie [1978], adjustable thresholds were added for errors in lane position and total curvature error. The two thresholds were adjusted so that the lane position variance in RORSIM would be close to that reported for the human subjects in Carson and Wierwillie [1978]. The RORSIM driver's behavior is probably typical of some human drivers under some circumstances, but it certainly does not represent the entire range of human behavior. Fixed tolerance thresholds were used throughout this study for what is called "normal" driving. It is justifiable for the comparisons that are made in this study, but a much wider and more realistic range of behaviors should be studied before forming firm conclusions on, for example, false alarm rates.

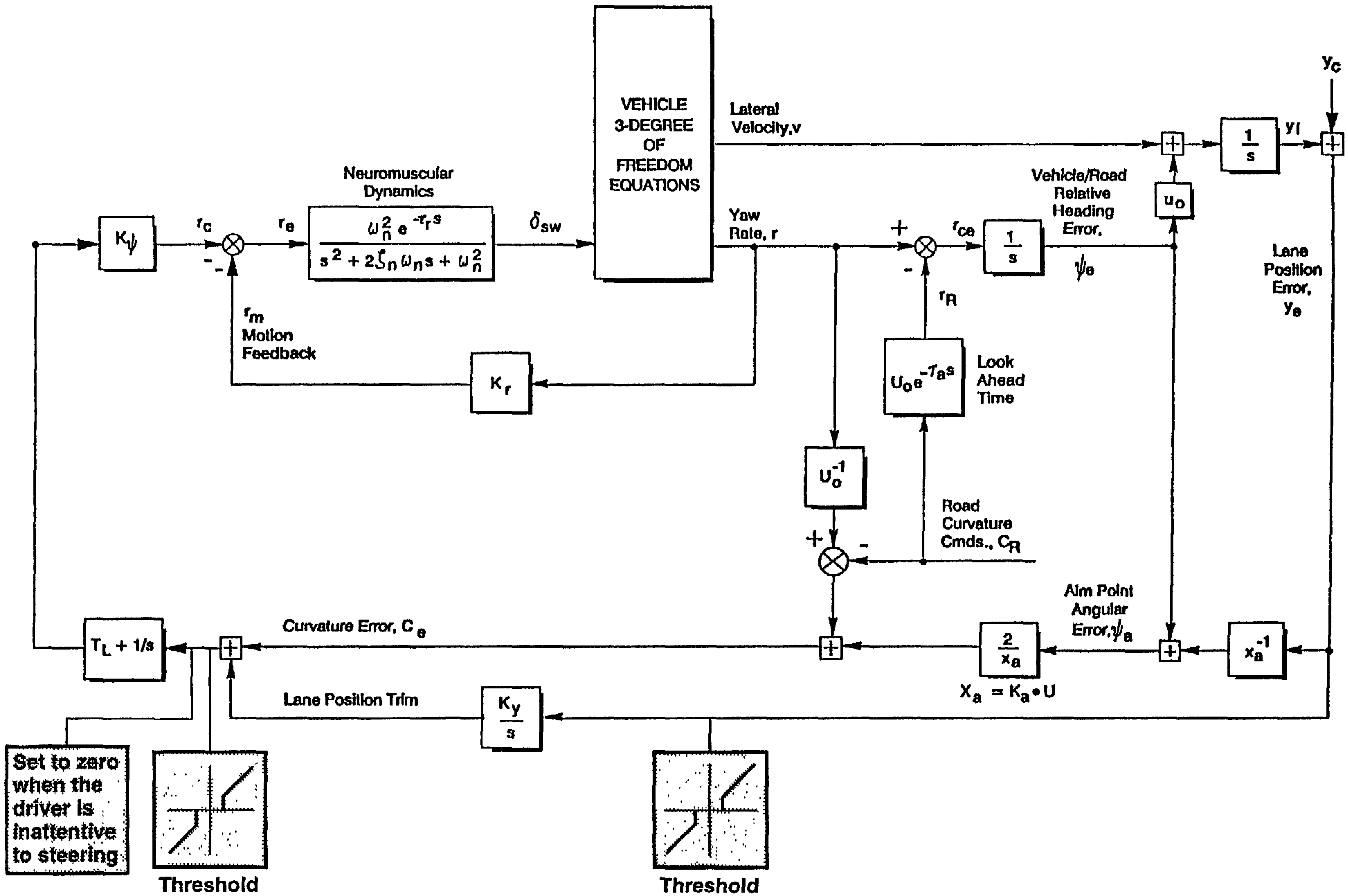


Figure 5-3 BLOCK DIAGRAM OF THE VDANL CLOSED-LOOP STEERING (DRIVER) MODEL

Potential roadway departure situations were established by simulating a brief period of driver inattention to the driving task. Inattention was modeled by holding the driver's controls constant, despite any changes in the vehicle's state. During a period of inattention to steering, the handwheel angle remains fixed. During a period of inattention to speed (such as failing to notice a sign warning of a curve), the throttle position remains fixed. Mathematically, this was done by setting the steering or speed error term to zero while the driver was inattentive. Inappropriate inputs (for example, a gross steering change while the driver reaches across the car) were not modeled. When the driver reacts to a warning, the driver resumes adjustments to the handwheel and throttle. The driver parameters that were in effect before an inattentive period are the sarne that are reinstated after a warning; (i.e., there is no provision for a startled driver).

A normal, healthy driver was modeled by selecting the 50-th percentile reaction times for steering and braking (0.82 and 1.2, respectively). The steering reaction times were taken from Figure 5-4, which was reconstructed from data reported by Malaterre & Lechner [1990]. The braking reaction times were taken from Figure 5-5, which was measured by Sivak et al [1982]. At the time the Run-Off-Road countermeasure studies were performed, little or no data were available on reaction times in exactly the situations being modeled. However, we believe that these data are reasonable. An unconscious driver would have infinitely long reaction times. A drunk driver can be modeled by longer than "normal" reaction times, lower crossover frequency, and wider intolerance bands to simulate the results of Allen et al [1975].

5.6 Roadway Model

The terrain and surface property model supplied with VDANL were used in RORSIM. The elevation, coefficient of friction, and coefficient of rolling resistance can be independently set at each of the four tires to model arbitrary road surfaces. To afford convenience for the RORSIM user in specifying roadways, a restricted yet flexible model of the roadway has been provided. The plan of this roadway, as shown in Figure 5-6, is a straight segment, a spiral entry to a curve, a constant-radius curve, a spiral exit, and finally a straight section. The five segments can be of any length, and the curvature can be any desired reasonable value. The curve can be to the right or the left. As it currently stands, RORSIM does not permit S-curves when the menu interface is used. The sections of the road model are shown in Figure 5-7. There are a two-lane road, a shoulder, and a run out area beyond the shoulder. The surface properties of the sections can be specified independently. There is a slope (crown) for the straight segment and a separate slope (superelevation or bank) for the curved segment. The elevations linearly transition within the spirals; the center of the road remains at a constant elevation, unless there is a grade. A constant up or down grade can be specified, but none was used for any of the simulations in this report. Details of the roadway model's capabilities and instructions on how to specify roadways are presented in the RORSIM User's Manual.

5.7 Environment Model

Most of the simulations in this task were run on a model of a clear, sunny day. Provisions were made to model a slippery road surface or impaired visibility. Wet or icy conditions can be

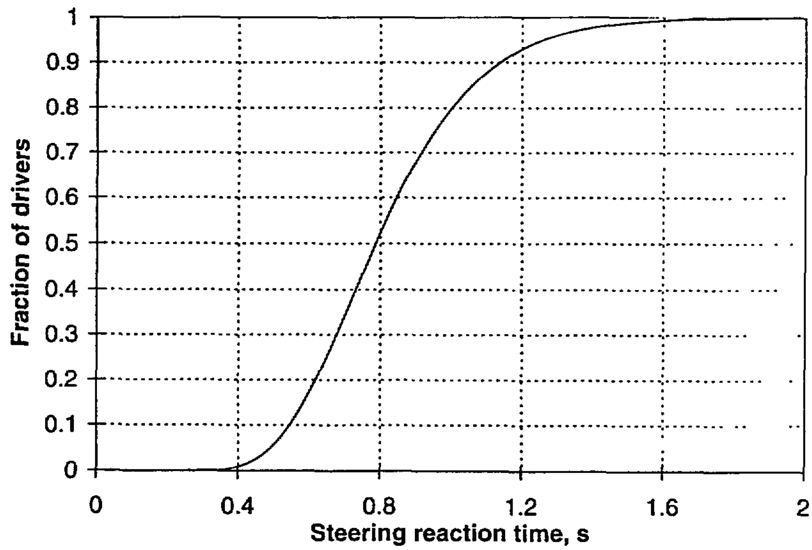


Figure 5-4 CUMULATIVE DISTRIBUTION OF STEERING REACTION TIMES (AFTER [MALATERRE AND LECHNER, 1990])

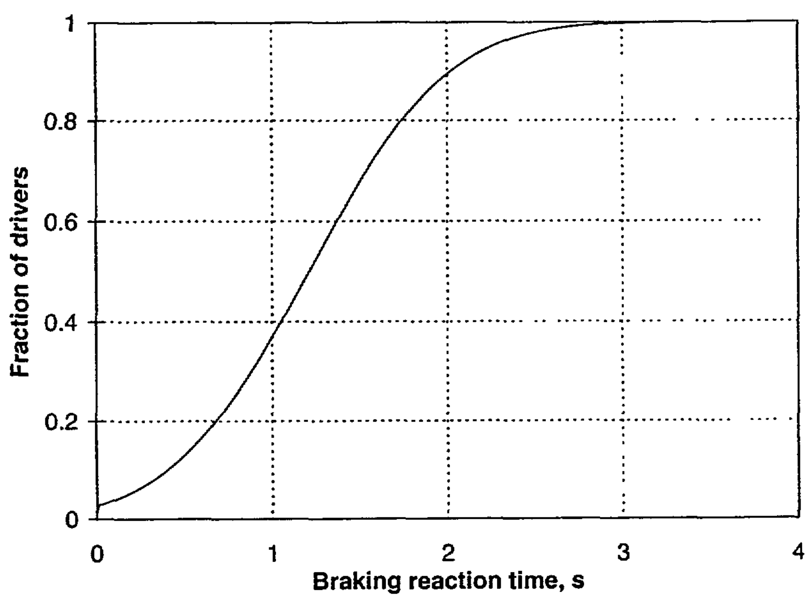


Figure 5-5 CUMULATIVE DISTRIBUTION OF BRAKING REACTION TIMES (AFTER [SIVAK, 1982])

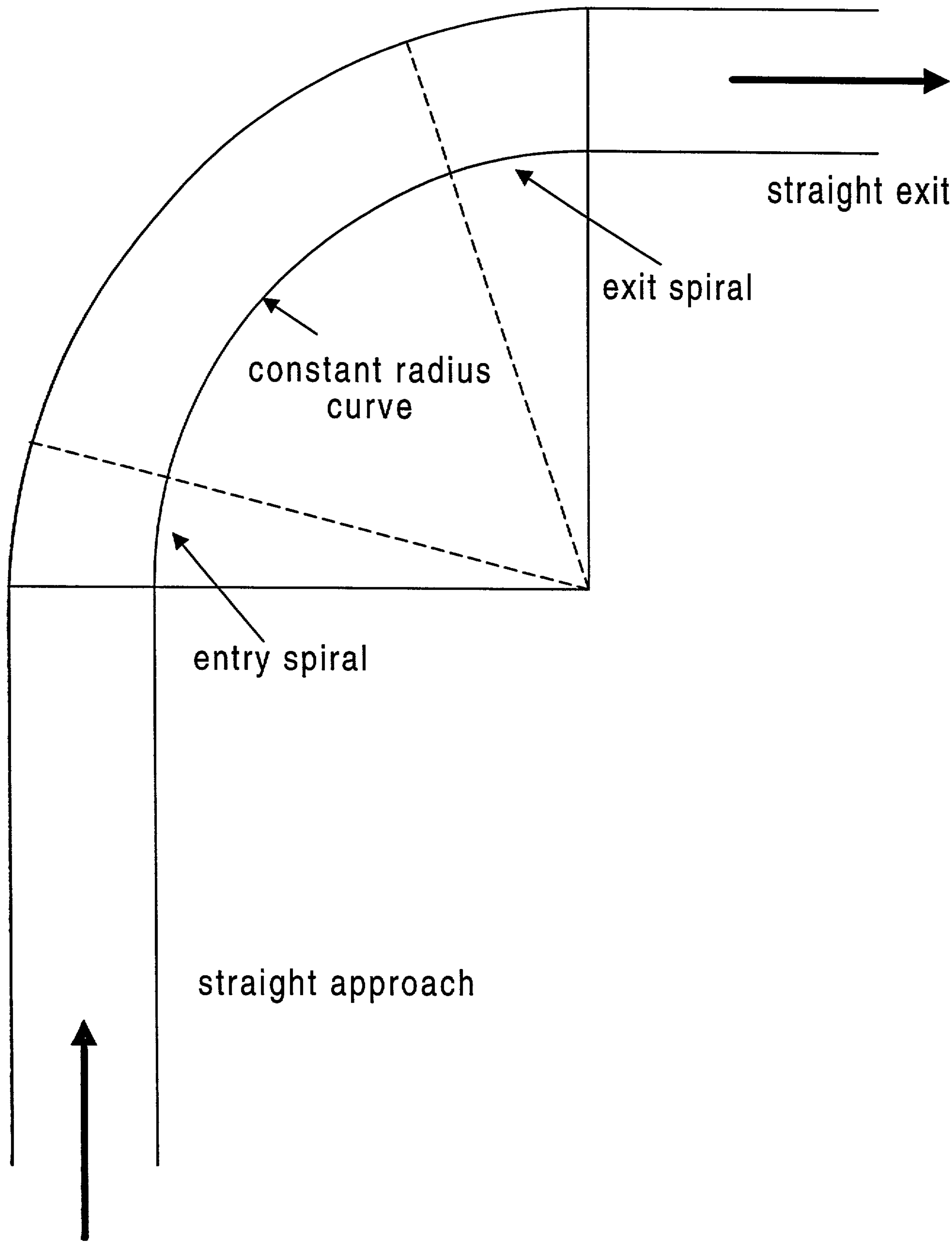
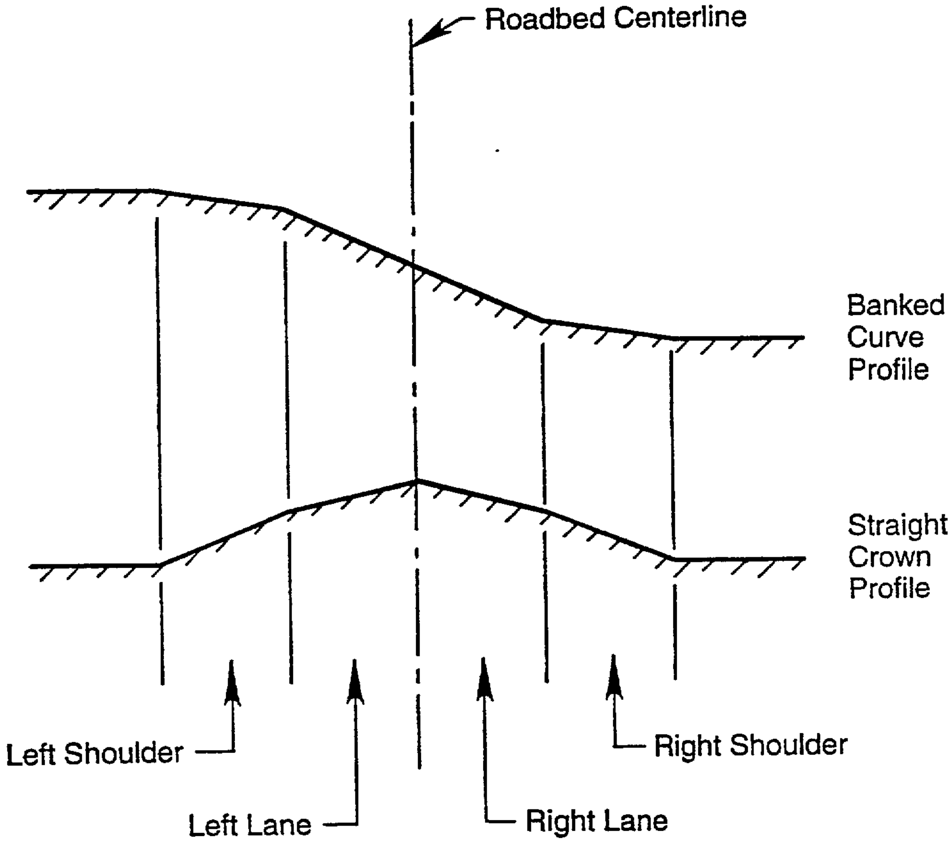


Figure 5-6 PLAN OF THE GENERIC ROADWAY USED IN ROSIM



For Straight Crown:

Slope of right lane = -slope of the left lane
Slope of right shoulder = -slope of left shoulder

For Banked Curve:

Slope of right lane = +slope of left lane

Slope of right shoulder = +slope of left shoulder

Figure 5-7 SECTIONS OF THE GENERIC ROADWAY USED IN FORSIM (ELEVATIONS ARE GREATLY EXAGGERATED)

modeled by reducing the coefficient of friction on the road and shoulder. A soft or muddy shoulder might have a higher rolling resistance than a paved or firm shoulder. The roadway shown in Figure 5-6 has constant surface conditions along the road, shoulder, and run out areas; there is currently no provision for patches of ice.

Impaired visibility can be modeled by applying noise to the vision sensor outputs. The sensor noise due to impaired visibility was obtained by transforming roadway imagery, acquired by a video camera during conditions of good visibility, to degraded imagery that corresponds to a specified level of adverse weather (e.g., 1/2 inch rain per hour). The methodology to achieve this transformation is . described more fully in the Task 3 final report of the Single-Vehicle-Roadway-Departure project.

The accuracy by which the sensor/image processing system can measure the center point of the subject vehicle's travel lane ahead of the vehicle decreases as the visibility range decreases. The visibility range is a function of the weather conditions (i.e., as the level of adverse weather becomes more intense, the visibility range decreases, and it becomes harder to see).

The performance degradation is not linear. The performance is only slightly affected by degraded conditions in which the visibility is more than 1,300 ft. Performance is affected significantly when the visibility is reduced too less than 1,000 ft. When visibility is reduced to 300 ft, performance is substantially degraded.

5.8 Overview of Program RORSIM

The heart of RORSIM is the VDANL vehicle model with the enhancements to model the driver and countermeasure systems. A menu program sets and organizes parameters that define a situation to be modeled. A separate post-processing program can plot vehicle positions to help visualize the trajectory.

Figure 5-8 is a high-level block diagram of the entire suite. A user begins with the menu program to enter values for speed, road design, environmental conditions, driver conditions, countermeasure settings, and all other conditions. These values are stored in a group of data files. If the user wishes, the menu can chain directly to the simulation program to run the case that has been established. In the figure, the enhancements are in a function USER MODULE, which is called from "breakpoints" in VDANL. The results can be viewed with the graphics capabilities built into VDANL,, and can be saved in disk files for use in other programs, including the post-processing viewer.

The menu system has separate pages for the roadway, environment, driver, Run-Off-Road scenario, and countermeasure systems. The menu system and program architecture are described in much more detail in the RORSIM User's Manual, which is Volume II of this report.

5.9 Verification of RORSIM

A number of simulated maneuvers were executed with the vehicle model to verify its performance and to determine the capabilities of the vehicle and driver. Some of the results

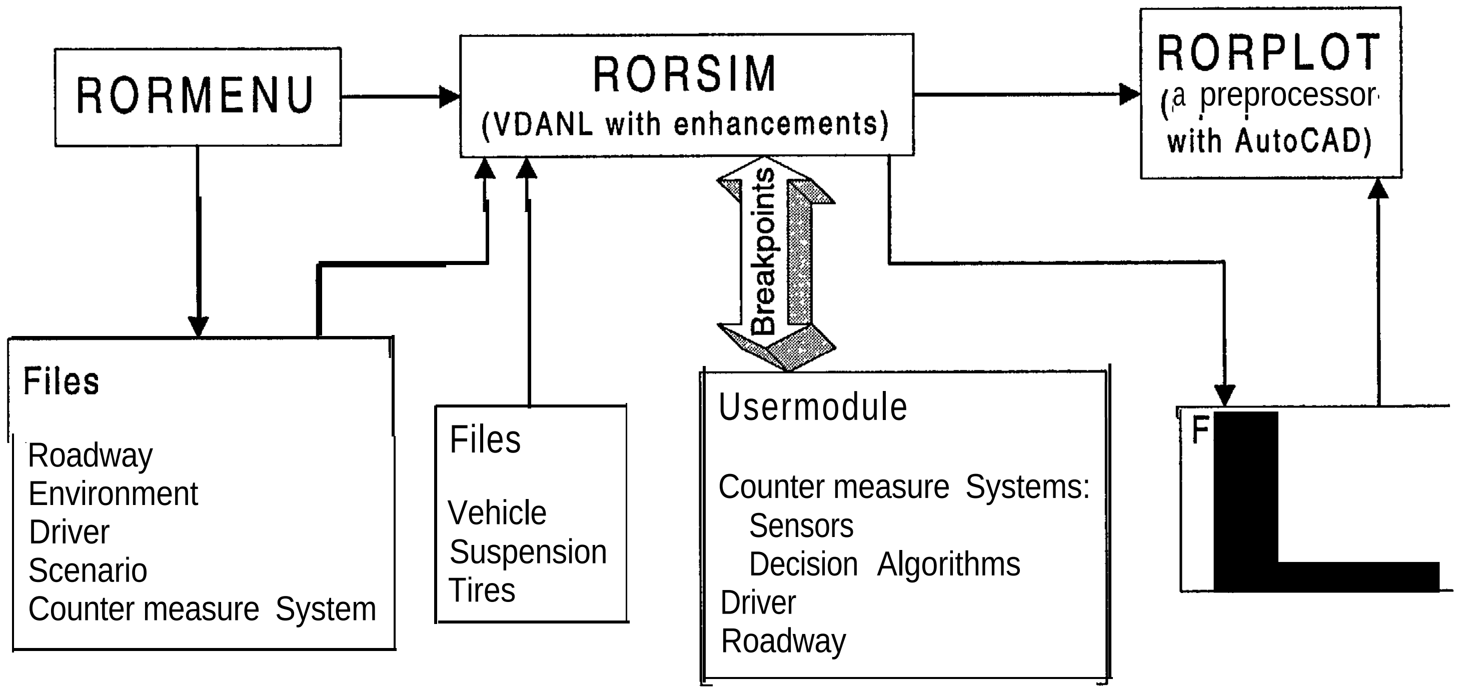


Figure 5-8 **HIGH-LEVEL BLOCK DIAGRAM OF THE RORSIM PACKAGE**

presented in this section will form the basis of detailed analysis discussed later in this report.

The cornering capability of the vehicle was determined by simulating driving in a banked, fixed-radius curve at increasing speed. The curve for this maneuver had a constant radius of 1000 ft, after a short entry. Two terrains were simulated: one flat with no superelevation and one with 4 percent favorable superelevation. Both terrains were simulated dry (coefficient of side friction is 0.85) and slippery (coefficient of side friction is 0.20). Figure 5-9 shows the increasing speed of the vehicle as a function of time. As was expected, the vehicle could stay in either curve when the road was dry. The handwheel angle calculated by the driver model to keep the vehicle in the curve is plotted in Figure 5-10 for all four cases. Note that the required handwheel angle increases with the speed. Slightly less steer angle was required in the banked curve. The two thick lines that suddenly increase around 55 s represent the slippery surface, where the vehicle could not maintain the 1000-ft radius above a limiting speed. The formula for calculating the required side friction factor, given a speed, radius, and superelevation, is [AASHTO 1994, p. 143].

$$f = \frac{V^2}{gR} - e \qquad 5\text{-}5$$

where

f = the side friction factor
e = the superelevation
R = the radius of curvature
V = the forward speed of the vehicle
g = the gravitational acceleration.

Figure 5-11 plots the instantaneously required side friction factor for the four road surfaces as the vehicle accelerated. The two thin lines in the figure representing dry road, increase until the maximum speed capability of the vehicle is reached. The two thick lines, representing the slippery road, end when the required side friction factor f reaches the road's available coefficient of friction of or 0.2. Of course, in a realistic driving maneuver, the exact point where one or more tires would lose traction depends on the weight distribution among the four tires. The weight distribution, in turn, depends on the loading of the vehicle, the roll stiffness, and the maneuver being executed (specifically, the yaw acceleration). Therefore, in this simple test case, the results of the VDANL model agree with the theory for the situation; therefore, the model could be applied to more realistic scenarios.

The above maneuvers were driver independent; they demonstrated the capability of the vehicle itself. The following discussion highlights the capabilities of the driver and countermeasure models.

Figure 5-12 shows the trajectory of the vehicle controlled by the driver model as it travels at 88 fps (60 mph) on a straight, crowned road. The paths of the vehicle center as well as the left front and right front tires are shown. The vehicle does not follow a perfectly straight line but meanders or wanders somewhat, to mimic the behavior of a human driver. In this report, vehicle paths such as those shown in Figure 5-12 are referred to as "normal" driving. A roadway departure

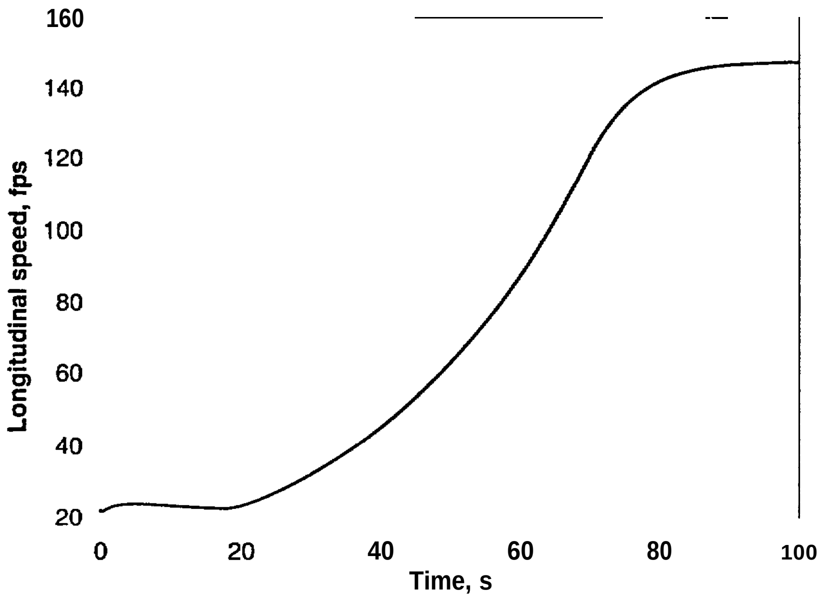


Figure 5-9 SPEED PROFILE USED IN THE INCREASING-CURVATURE SIMULATION

trajectory can be generated by causing the driver to become inattentive to steering at some point. When the driver is not paying attention to steering, in this model, the handwheel angle is fixed along the meandering trajectory. Different trajectories can be generated by imposing inattention at different times. Figure 5-13 shows the vehicle center path for four crash trajectories as well as the normal path. In three of the paths, the vehicle drives off the right side of the road (positive y is to the right), and one departure is to the left.

If the driver regains attention and resumes controlling the steering in time, the vehicle will not depart its lane, or at least it will not get too far out of its lane. One feature of RORSIM is the capability to "turn on" the driver at a predetermined time. By varying the instant when the driver resumes control of the vehicle, the maximum lane deviation in a simulation can be varied. Figure 5-14 shows the right front tire coordinate of one crash trajectory and several recovery trajectories. In all of these simulations the driver relinquished control at the same moment, but the duration of the inattentive period was different. The extra heavy line in the figure reaches a maximum tire position of 6 ft. Therefore, if the lane width were 12 ft, this represents the case where the vehicle just misses departing its lane. The moment when the driver resumes steering the vehicle so that the maximum tire position is 6 ft is termed the "last chance to act." If the vehicle is to stay in its lane at all times, the countermeasure system must warn the driver before the last chance to act, to allow for reaction time. The maximum tolerable lane excursion, of course, depends strongly on the situation (i.e., whether there is a wide, paved shoulder, a guardrail, a roadside obstructions oncoming traffic, etc.).

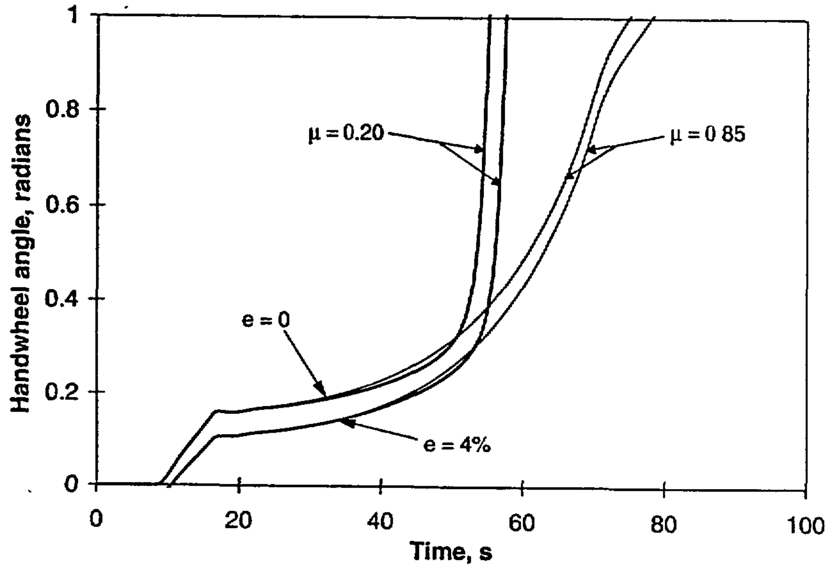


Figure 5-10 HANDWHEEL ANGLE REQUIRED TO MAINTAIN THE DESIRED RADIUS IN THE INCREASING-CURVATURE SIMULATION

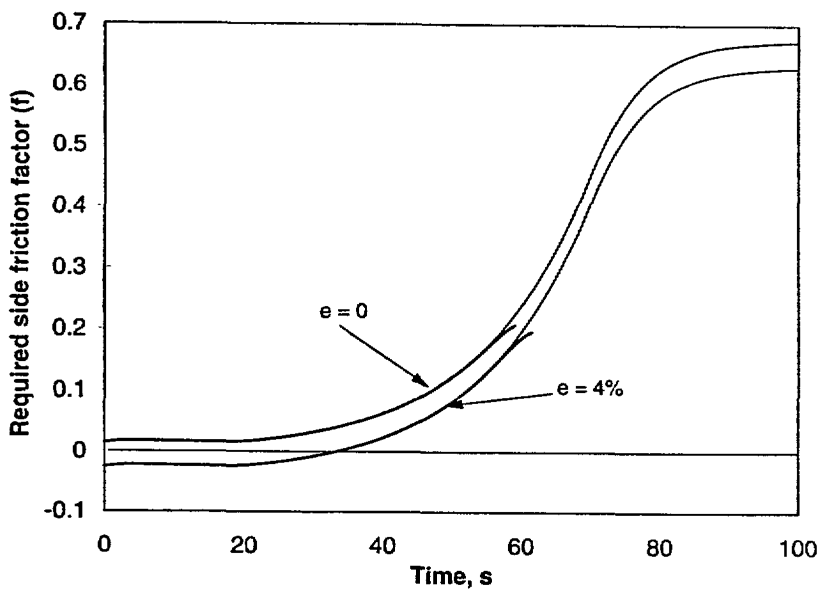


Figure 5-11 SIDE FRICTION FACTOR REQUIRED TO MAINTAIN THE DESIRED RADIUS IN THE INCREASING-CURVATURE SIMULATION

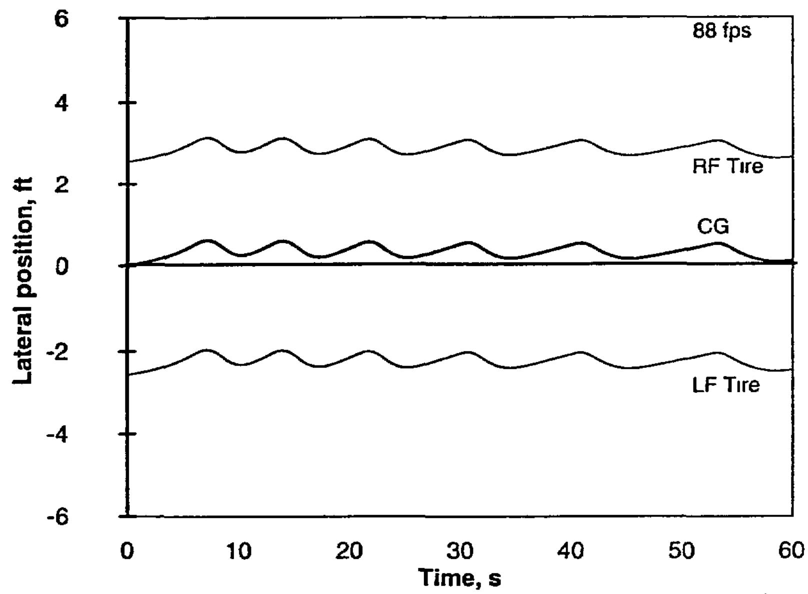


Figure 5-12 TRAJECTORY OF THE VEHICLE CONTROLLED BY THE DRIVER MODEL AS IT TRAVELS AT 88 FPS (60 MPH) ON A STRAIGHT, CROWNED ROAD

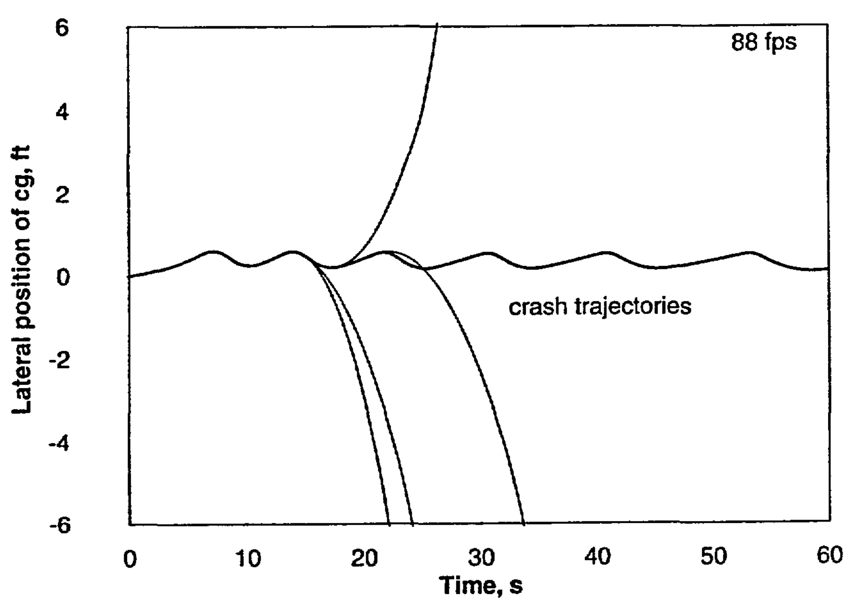


Figure 5-13 FOUR POSSIBLE CRASH TRAJECTORIES. THE PATHS ARE GENERATED BY MAKING THE DRIVER INATTENTIVE TO STEERING AT DIFFERENT TIMES ON THE "NORMAL", CONTROLLED TRAJECTORY, WHICH IS SHOWN IN BOLD

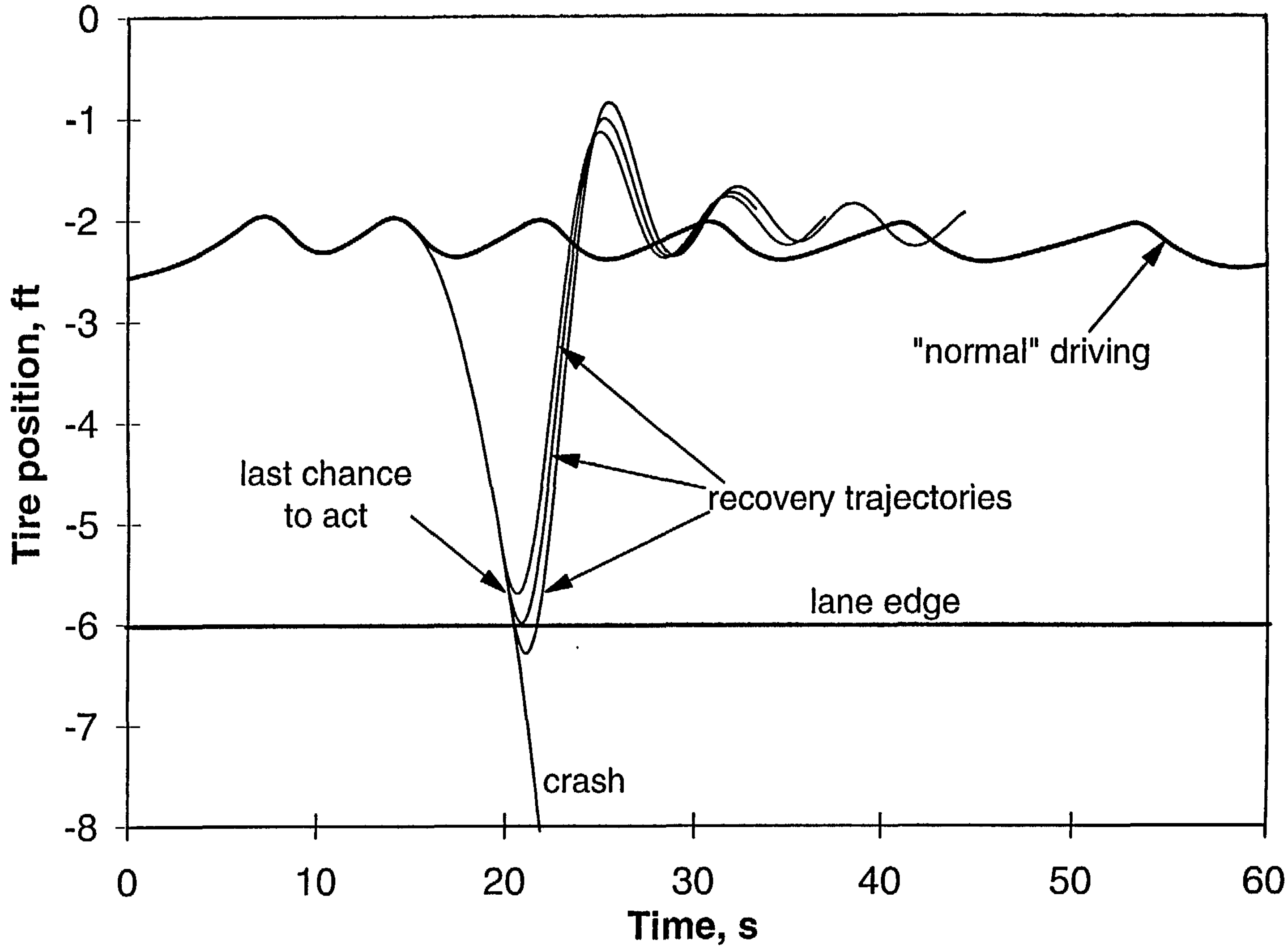


Figure 5-14 SEVERAL POSSIBLE RECOVERY TRAJECTORIES FROM A SINGLE CRASH-BOUND TRAJECTORY. IF THE DRIVER RESUMES ATTENTION TO THE STEERING TASK AT THE "LAST CHANCE TO ACT", THE RIGHT FRONT TIRE JUST TOUCHES THE LANE EDGE AT 6 FT

As an example of countermeasure system performance, Figure 5- 15 shows one version of the forward looking countermeasure with the TTD function for “normal” driving and for a crash trajectory. The minimum TTD (in this case) in normal driving is 4.77s. If one second is allowed for driver reaction, then the driver would need to be warned (in this case) at a TTD value of 2.60s. This is identified in the figure as “time to warn.” Note that, in the figure, the TTD value at “time to warn” is lower than the lowest TTD value observed in “normal” driving. A warning threshold might be set at a TTD value between 4.77 (normal) and 2.60 (time to warn).

Measurement error or other factors may produce uncertainty in the minimum normal and time-m-warn TTD values. The time that elapses, when the vehicle is on the crash trajectory, between the last occurrence of “normal” TTD (at 15.15s) and the “time to warn” (at 16.95s) is identified in the figure as the “time margin.” This is a measure of the ability of the countermeasure system to distinguish normal driving from near-departure driving. The concept of time margin imposes the constraint that there be no false alarms and that the vehicle must stay completely in its lane for successful recovery. This is a worthy goal, but it may not always be necessary. An occasional warning to a driver not on a departure trajectory may be tolerable, even desirable [Tijerina 1995].

Of course, this analysis of Figure 5-15 must be qualified in that the “normal” trajectory in this simulation does not encompass all normal human driving behavior. Furthermore, the value of TTD at “time to warn” depends strongly on the nature of the departure trajectory. The values that TTD and TLC can take under different “normal” and emergency driving situations is the subject of extensive discussion in the next section.

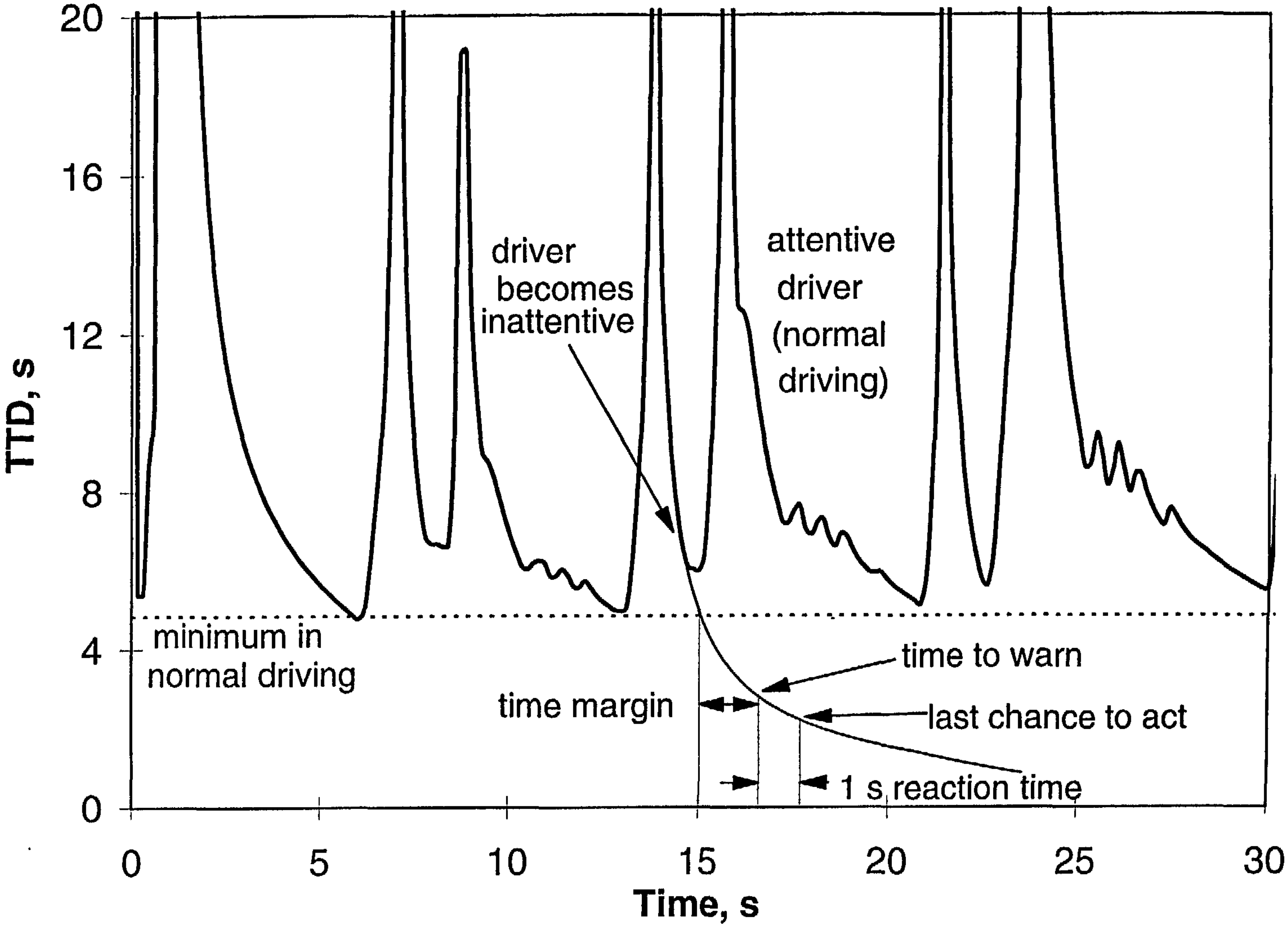


Figure 5-15 TTD (TIME-TRAJECTORY-DIVERGENCE) FUNCTION FOR THE "NORMAL" DRIVING CASE OF FIGURE 5-11 AND ONE CRASH TRAJECTORY OF FIGURE 5-13

6.0 Results: Lateral Countermeasure Systems

The lateral (steering) and longitudinal (throttle and brake) countermeasure systems were analyzed separately because the nature of run-off-road crashes addressed by the two classes of countermeasure systems is different. The general scenario where a lateral countermeasure system would be effective is a situation where the driver drifts off the roadway. Driver inattention is frequently the cause of this type of crash. It may result from a number of factors (e.g., retrieving a fallen object, adjusting the radio, etc.). Alternatively, these crashes sometimes occur because the driver relinquishes steering control due to some physical condition such as drowsiness or a seizure. In any case, the countermeasure system must restore the driver's attention in time to steer the vehicle back on the road. If the driver fails to respond to the warning within a reasonable period of time, the system may intervene and take steering action itself.

Two types of lateral countermeasure systems, corresponding to systems with and without forward preview, were studied in parallel. The lateral countermeasure with forward preview (forward-looking) uses the Time to Trajectory Divergence (TTD) algorithm to decide when to trigger an alarm. The lateral countermeasure without forward preview (downward looking) uses the Time to Line Crossing (TLC) algorithm to decide when to trigger an alarm. The details of how the systems work were presented in Section 5.3.

The goal of this work was to identify a set of performance guidelines characterizing the dynamic circumstances in which a driver should be warned of an impending roadway departure. To begin, the levels of TTD and TLC functions that commonly occur in safe driving in the RORSIM model and in emergency conditions were noted. Tentative warning threshold levels were selected to provide adequate warning in emergency situations but reasonably false low alarm frequencies in safe driving situations. The propensity for false alarms was studied by running the RORSIM vehicle along a path taken by a human driver in an actual highway segment. To assess the effectiveness of the two systems, they were compared with an existing system, which was modeled as a form of the downward-looking countermeasure.

6.1 Preliminary Analysis of TTD and TLC Levels

The analysis of the two lateral systems began by studying how the TTD (Time to Trajectory Divergence) and TLC (Time to Line Crossing) functions behave in normal driving conditions. Familiarity with the functions is essential for understanding their behavior in near-departure situations. Furthermore, warning criteria must be selected so that they do not trigger alarms or intervention during ordinary driving. The critical part of the analysis was identifying the driver's last chance to prevent a roadway departure. The final step in this preliminary analysis was to measure each system's ability to distinguish between normal and emergency situations.

The desired result of this preliminary analysis was a selection of TTD and TLC levels at which a system would warn a driver or intervene in steering. The forward-looking system required further analysis to select the best value for an extra parameter, the look-ahead distance.

The analysis was carried out for a variety of speeds on a 1000-ft-radius curve and for a vehicle traveling at 88 fps (60 mph) on road segments of different curvature. Table 6-l indicates the cases that were analyzed and provides the essential design properties of the road segments. Note that the 1000-ft-radius curve is identical to a curve on the simulator course used in Task 3 of this project. This, in turn, was based on Task 1 results indicating this is the type of curve typically associated with Run-Off-Road crashes. On each curved segment, the driver moved two feet toward the inside of the curve to simulate typical "curve cutting" driver behavior. To establish levels in "normal" driving, the curves were all 90 degrees--a right angle turn to the right. The simulations of departures and warnings were run in continuous curves. The approach and entry spiral were identical for normal and emergency situations, but the road remained curved indefinitely for all but the normal-driving simulations.

Table 6-1.
Cases Used to Study the Performance of the Lateral Countermeasure Systems

Road Parameters			Vehicle Speeds		
Curvature	Superelevation	Entry Spiral Length	44fps	66fps	88fps
Straight road	2.08% (crown)	--			X
4000 ft curve	4.0%	176 ft			X
1000 ft curve	4.0%	176 ft	X	X	X
800 ft curve	9.5%	250 ft			X

For the effectiveness estimates of Section 6.3, each of the combinations marked with an X was simulated for the folowing categories:

Steering Reaction Time	SNAP	Forward Looking		Downward Looking	
		Warning	Intervention	Warning	Intervention
0.82 s (50th percentile	X	X		X	
1.13 s (90th percentile)	X	X		X	
no reaction (incapacitated)			X		X

6.1.1 Normal Driving Patterns in RORSIM

The path of a "normal" RORSIM driver on a straight, crowned road at 88 fps (60 mph) was shown in Figure 5-12. The instantaneous TTD as a function of time for this case is plotted in Figure 6-la . Note that the function is occasionally very high at points where the driver's actual curvature and the system's desired curvature are momentarily identical. Generally, the vehicle is drifting toward one side of the road until the TTD becomes large and then for a while it is drifting toward the opposite side of the road. The direction of drift cannot be determined from this plot alone, though. The TLC function for this same path is plotted in Figure 6- 1 b. The TLC function is defined such that a positive value indicates that the vehicle, if it continues at a constant speed and curvature, will depart the lane to the right, and a negative value indicates that the vehicle is bound for a departure to the left. As the vehicle oscillates about perfect alignment with the road, the projected departure point alternates sides, giving this characteristic shape of TLC curves.

The path of a normal RORSIM driver on a 1000-ft-radius curve at 44 fps is shown in Figure 6-2. The road segment is like the rural primary curve in the driving simulator studies in Task 3 of this project: lOOO-ft radius, 4 percent superelevation, 176~ft spirals, 90-degree bend. The simulated vehicle took the curve at 44 fps (30 mph), which is the posted speed. The simulation was planned so that the vehicle would move 2 ft toward the inside of the curve as it entered the curve and return to the lane center as it exited the curve. The graph in Figure 6-2 shows the trajectory of the right front tire and the road curvature as functions of time during the simulation. In the scale for the tire trajectory, 0 is the lane center and 6 ft is the lane edge. The tire came within a foot of the inside lane edge as the vehicle negotiated the curve. The TTD function for this path is plotted in Figure 6-3a. The TLC function for this path is plotted in Figure 6-3b.

In Figure 6-3a, the lowest TTD observed in normal driving (at a look-ahead distance of 66 ft) was 2.107 s. In Figure 6- 3b, the lowest (absolute value) TLC was 2.68 s. In a similar manner, the lowest values of TTD and TLC in normal driving were noted for all of the cases in Table 6-l. While these paths of "normal" driving represent a reasonable sample of curve negotiation trajectories, they do not represent all possible trajectories a driver could follow through a curve. If a system is to cause no false'alarms during "normal" driving, then the warning thresholds must be below the observed minimum values. The values for the cases will be presented in Table 6-2 in the following subsection.

6.1.2 Crash Trajectories in RORSIM and "Last Chance to Act"

Critical to designing a countermeasure system is determining the point when a driver must be warned so that a road departure can be avoided. The concept of "last chance to act" was introduced with Figure 5-14. For a given departure trajectory, cases were simulated with the inattentive period ending at one of several predetermined times. The task was to identify the time at which resumption of steering control leads to the vehicle tire's just touching the lane edge before recovery.

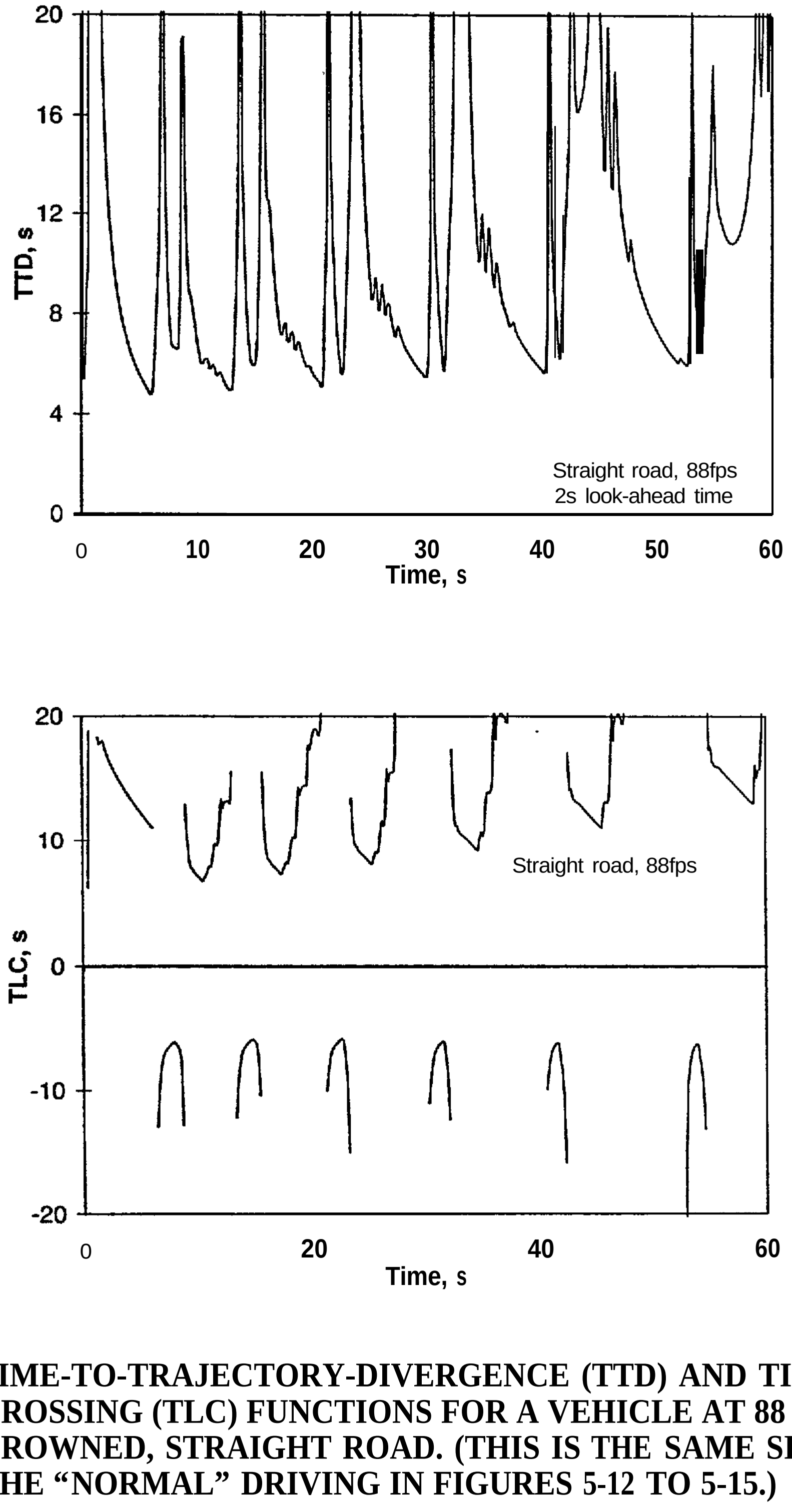
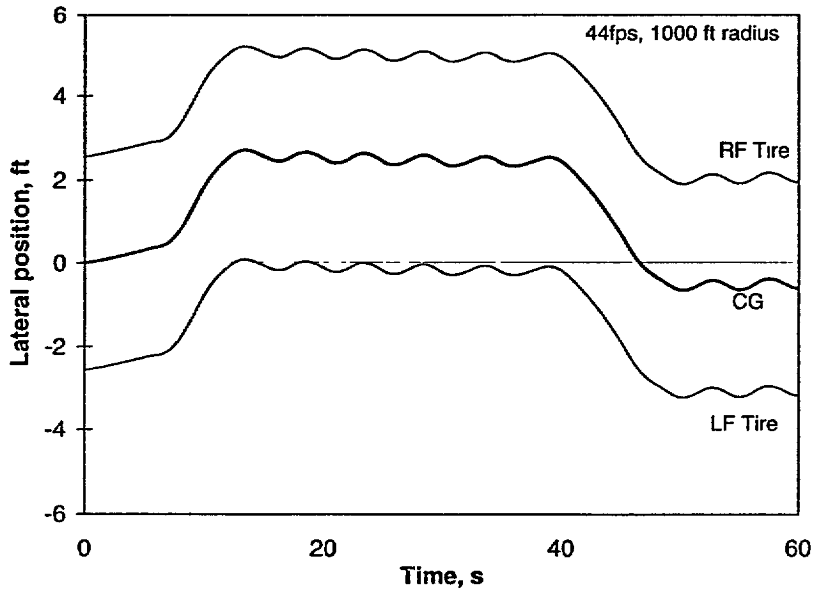


Figure 6-l TIME-TO-TRAJECTORY-DIVERGENCE (TTD) AND TIME-TO-LINE CROSSING (TLC) FUNCTIONS FOR A VEHICLE AT 88 FPS ON A CROWNED, STRAIGHT ROAD. (THIS IS THE SAME SIMULATION AS THE "NORMAL" DRIVING IN FIGURES 5-12 TO 5-15.)



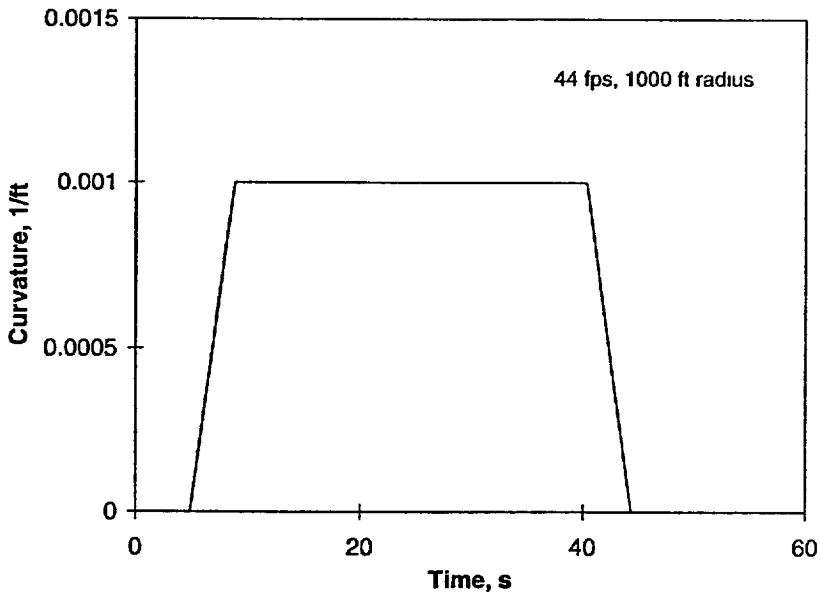


Figure 6-2 TRAJECTORIES OF THE VEHICLE CENTER OF GRAVITY AND BOTH FRONT TIRES AS IT SUCCESSFULLY NEGOTIATES A 1000-FT-RADIUS, RIGHT-ANGLE CURVE AT 88 FPS, CUTTING THE CURVE BY 2 FT. THE INSTANTANEOUS ROAD CURVATURE IS SHOWN IN THE LOWER FIGURE

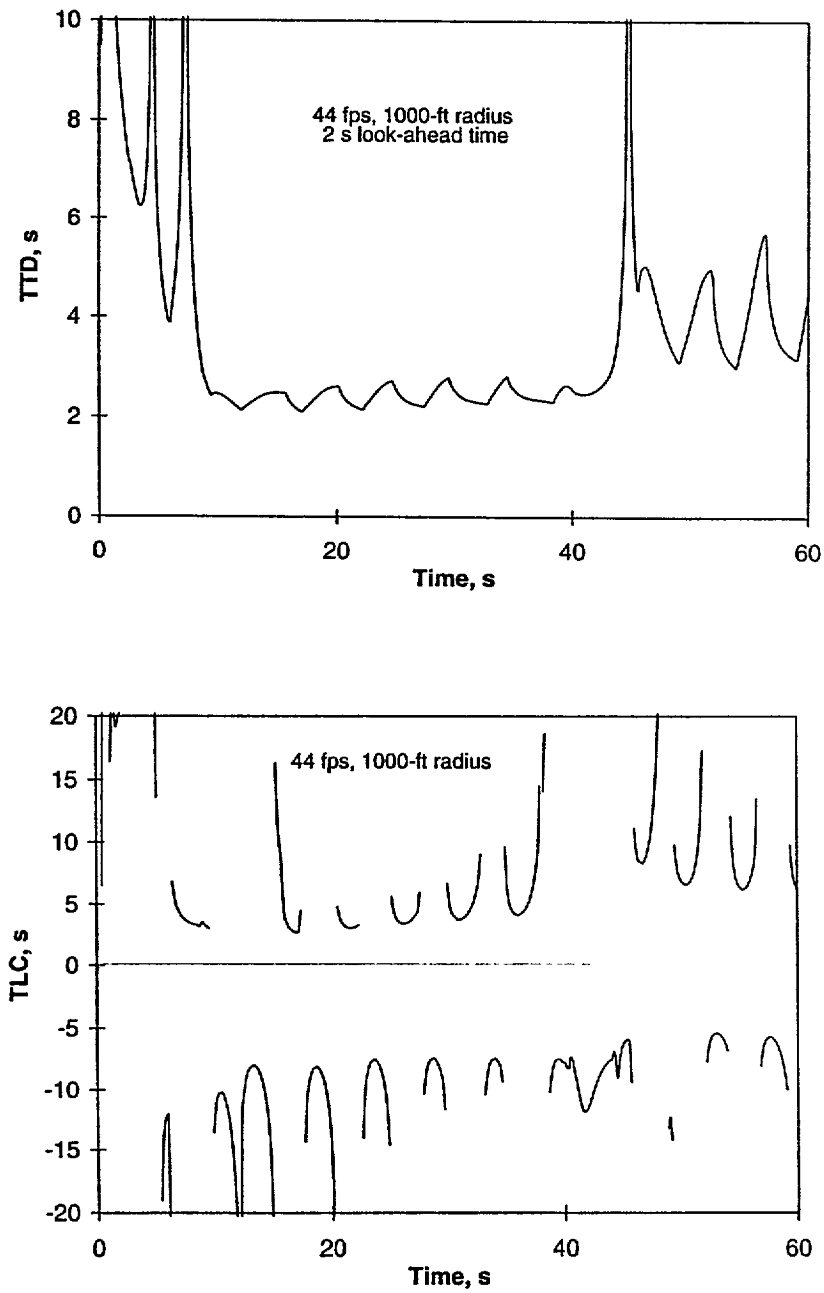


Figure 6-3 TTD AND TLC FUNCTIONS FOR THE SIMULATION IN FIGURE 6-2

For four departure trajectories in each of the cases in Table 6-1, the last chance to act was identified. Figure 5-13 showed how four potential crash trajectories were generated from one "normal" trajectory.

Of course, if a driver reacts with a more aggressive recovery maneuver than the RORSIM model, initiation of the maneuver can be delayed somewhat. Also, a lane departure of only a few inches is usually not disastrous, especially for roadways with a shoulder. A recovery maneuver that leads to only a slight lane deviation would probably be successful in nearly every instance. As with the patterns of "normal" driving, the data for "last chance to act" are justifiable if not typical, but they are by no means representative of all drivers or of all situations.

Because of a human's finite reaction time, the driver must be warned of a potential departure before the last chance to act occurs if a crash is to be avoided. A one-second reaction time for steering is adequate for approximately 85 percent of drivers tested by [Malaterre & Lechner, 1990]. The state of the vehicle at the time when the warning should be issued was studies to identify the conditions that should prompt a warning. Any proposed countermeasure system should provide a warning to the driver when the vehicle state (combination of speed, heading error, TTD value, or other quantities) reaches threshold conditions at some point before the driver's last chance to act.

The necessary warning levels of TTD and TLC were the values calculated at 1 .O s before the "last chance to act." An active countermeasure system that provides steering control would have a nearly instantaneous reaction. If the system provided steering input approximately the same as the RORSIM driver model, it should intervene at the TTD and TLC levels at the last chance to act. The critical TTD and TLC values are summarized in Table 6-2. The table has three major columns, for 44 (30 mph), 66 (45 mph), and 88 (60 mph) fps. Table 6-2 has two major rows, for TTD and TLC. The minimum values of TTD and TLC observed in normal driving (as discussed in Section 6.1.1) at each of the three speeds are listed in Table 6-2. At each speed, there were four crash trajectories. Each crash trajectory had a TTD and TLC value at the last chance to act and at 1 .O s before the last chance to act (time to warn the driver). The "time to warn" and "time to act" values are tabulated. (For TTD, only one look-ahead distance is mentioned in the table. This distance was selected by the procedure discussed in Section 6.1.3). Also listed in the table are the warning and intervention thresholds that were eventually selected for the effectiveness study in Section 6.3. The thresholds were chosen low enough to avoid causing any action during RORSIM normal driving. Generally, the thresholds could be set high enough to prevent three of the four departures from each "normal" trajectory.

For each combination of speed and curvature, four crash departure trajectories were analyzed, as exemplified in Figure 5-13. The vehicle does not approach the edge at the same rate in all four trajectories. The departure may be rather gentle in one trajectory and rather sudden in another. A countermeasure system would ideally prevent all departures for a particular speed and curvature combination. To do so, the warning threshold must be set at the highest of the four values for each combination. While the "normal" driving analysis above established upper bound of the warning thresholds to avoid false alarms, the "last chance to act" analysis established an lower bound to

Table 6-2
Summary of TTD and TLC Levels in Normal Driving, Warning Conditions, and Last Chance to Act

		44 fps (30 mph)		66 fps (45 mph)		88 fps (60 mph)	
		observed in four potential crash trajectories	threshold selected for effectiveness studies	observed in four potential crash trajectories	threshold selected for effectiveness studies	observed in four potential crash trajectories	threshold selected for effectiveness studies
TTD	best look-ahead time distance	1.5 s (66 ft)		1 .0 s (66 ft)		1.0 s (88 ft)	
	minimum in "normal" driving	2.107		1.45		1.21	
	value at time to warn the driver	1.41 1.89 1.86 1.86	1.85	1.34 1.43 0.96 1.33	1.34	0.95 1.86 0.90 1.52	1.20
	value at time to act	1.22 1.65 1.77 1.77	1.65	1.07 1.25 0.88 1.23	1.20	083 1.41 0.83 1.38	1.00
TLC	minimum in "normal" driving	2.68		3.54		2.0	
	value at time to Warn the driver	1.51 1.70 1.48 1.44	1.50	2.82 1.81 1.48 1.35	1.80	1.79 0.83 1.66 1.42	1.80
	value at time to act	0.49 0.67 0.47 0.43	0.50	1.86 0.78 0.47 0.30	0.80	0.78 0.81 0.66 0.42	0.80

prevent roadway departures. The comparison of the upper and lower bounds is the next subject to be discussed.

6.1.3 Discrimination Between Normal and Emergency Situations

A countermeasure system must distinguish between ordinary driving maneuvers and departure-bound paths. Inevitably a system will occasionally sound a warning when the vehicle is perhaps near an edge but not in danger of departure, and occasionally permit the vehicle to depart the road by a small amount. Parameters for a system should be selected to minimize the rates of both late and unwarranted alarms. Under ideal conditions, the lowest value of TTD or TLC experienced in normal driving would be greater than the highest value when the driver must be warned. Thus, the threshold could be placed anywhere between the "normal" and "time to warn" values. Although bounding the threshold in this manner is not always possible, it is, nevertheless, the desired goal.

A measure of the separation between the "normal" and "time to warn" conditions is the time that elapses as the TTD or TLC function drops from normal to warning levels. The concept was introduced in Figure 5-15. This elapsed time is termed the "Time Margin." A high time margin means that the system can easily distinguish between normal and emergency situations. A very small time margin means that the system can quickly progress from what it believes to be normal driving to a condition where the driver must be warned. A small amount of measurement error or processing delay could cause a small margin to vanish. A negative time margin (time margin is less than zero) means that the required warning level (i.e., TTD or TLC) is higher than the value observed at least once in the corresponding normal driving courses.

The definition of Time Margin is further illustrated in Figure 6-4, where the TTD functions for two crash trajectories are plotted. The upper horizontal line in the figure is the lowest value of TTD that was observed when an attentive driver negotiated this section of simulated roadway. The warning threshold of the TTD function must be below this level to avoid false alarms. The "time to warn" the driver for the two trajectories are indicated in the figure. Because the first trajectory (dotted, on the left) has a higher TTD at "time to warn" than the second (right) trajectory, it controls the warning threshold. The threshold must be set at or above this value of TTD if the system is to warn the driver in time to prevent a lane departure. The lower horizontal line in the figure is at the minimum warning threshold. The Time Margin for each trajectory is the elapsed time as its TTD value drops from the upper horizontal line to the lower horizontal line. Note that the second trajectory has a shorter time margin, even though its TTD curve takes longer to drop from the upper horizontal line to its own "time to warn" point. The reason for this is that, to prevent a lane departure at this speed, the warning threshold must be set high enough to protect the driver on the first trajectory. The driver on the second trajectory would be warned before the actual last moment. A more sophisticated system might determine whether the vehicle's trajectory was more like the first or the second and adaptively adjust the warning threshold accordingly. Such systems were not considered in this phase.

In a few cases, the calculated time margin was extremely low. This was caused by one of the four departure trajectories having an unusually high TTD at the time to warn. The combination of orientation, position, look-ahead distance, and vehicle velocity was unfavorable.

Figures 6-6 shows the variation in TTD time margin as a function of look-ahead distance for speeds of 44 fps (30 mph), 66 fps (45 mph), 88 fps (60 mph), and 110 fps (76 mph) on the 1000-ft-radius curve. The four curves represent the four departure trajectories. Solid lines indicate departure to the right (the inside of the curve), and dotted lines indicate departure to the left (outside of the curve). The TLC time margins are plotted at the far right in each figure. Only one set of four is plotted because TLC does not depend on look-ahead time.

In the figure for the 44-fps vehicle on the 1000-ft curve, the time margin function is highest at about 1.5 s look-ahead time. This result suggests that for vehicles traveling at about 44 fps on a curve of about 1000 ft radius, the best look-ahead time would be about 1.5 s. Note also that the time margin is positive for all four departure trajectories. Therefore, to the extent that the conditions of the 44-fps simulation are representative of actual driving, the TTD countermeasure system could prevent 100 percent of the lane departures while maintaining a false alarm rate of 0 percent. The TLC time margin was positive for all four departure trajectories at 44 fps as well. The lowest TTD time margin is about the same as the lowest TLC time margin (both are about 0.7? s), so both systems have the potential of working equally well.

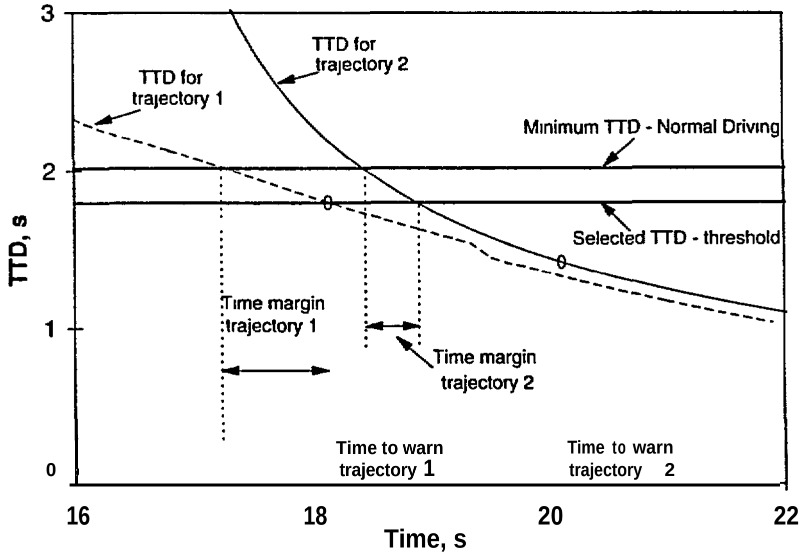
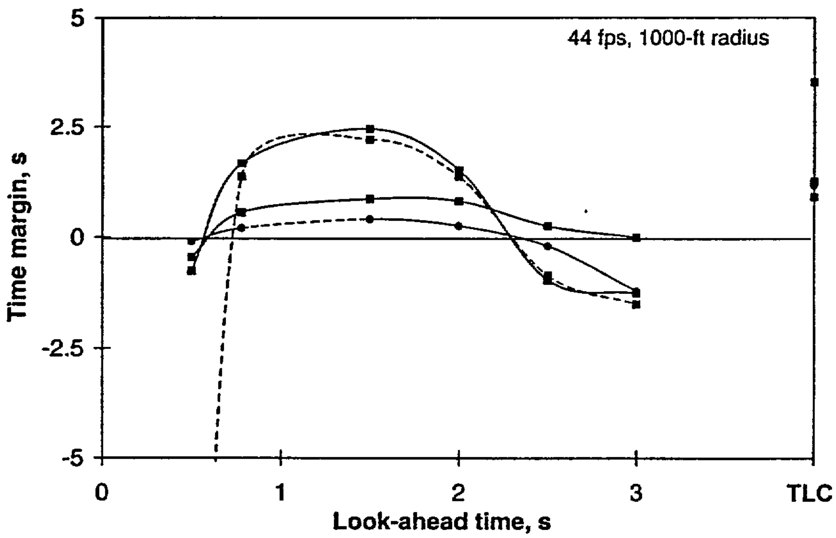


Figure 6-4 **TTD (TIME-TO-TRAJECTORY-DIVERGENCE) FUNCTIONS FOR TWO CRASH TRAJECTORIES. NOTE HOW THE TIME MARGIN FOR TRAJECTORY 1 IS SHORTER, EVEN THOUGH ITS TTD VALUE AT "TIME TO WARN" IS LOWER THAN TRAJECTORY 2'S**



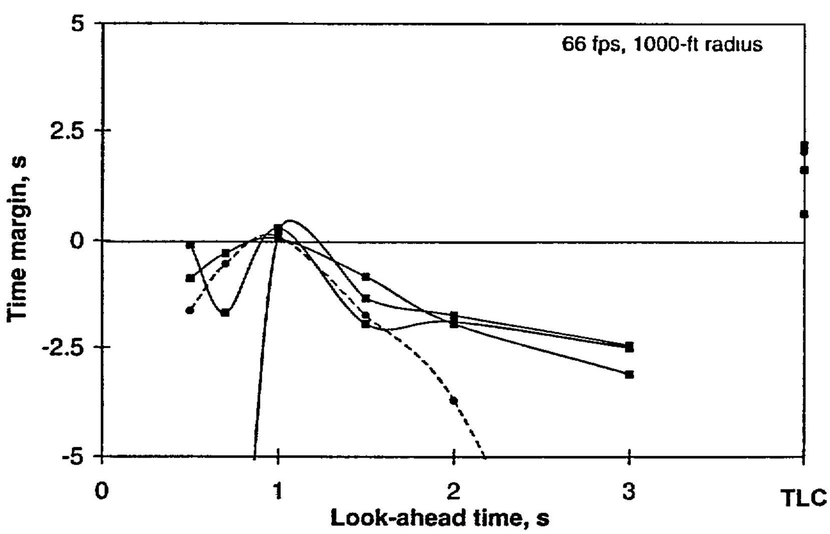
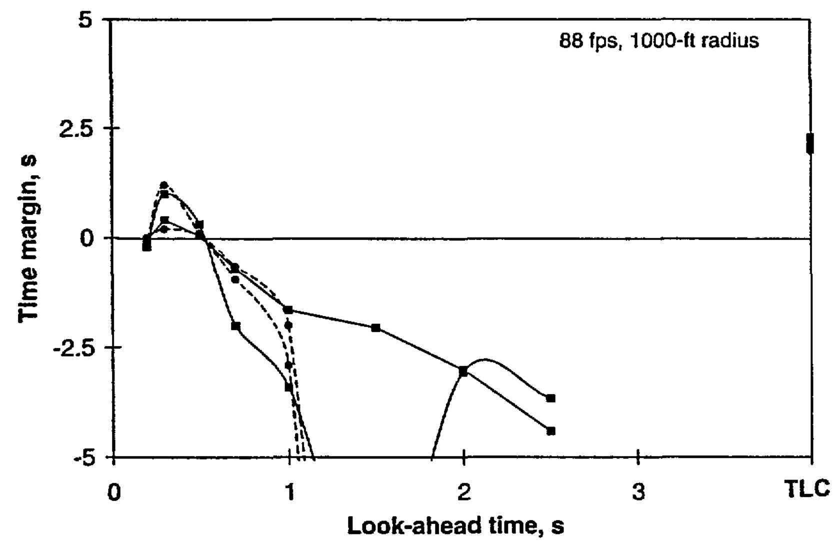


Figure 6-5 **TIME MARGIN PLOTS**



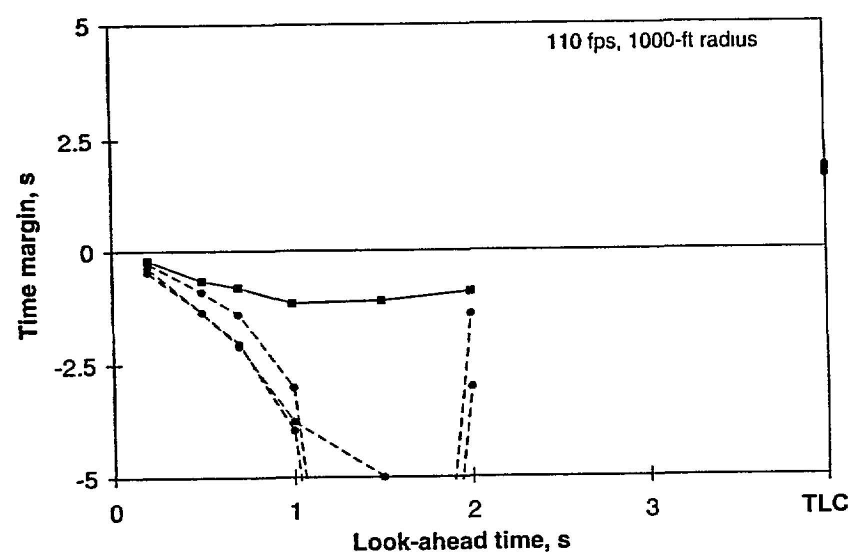
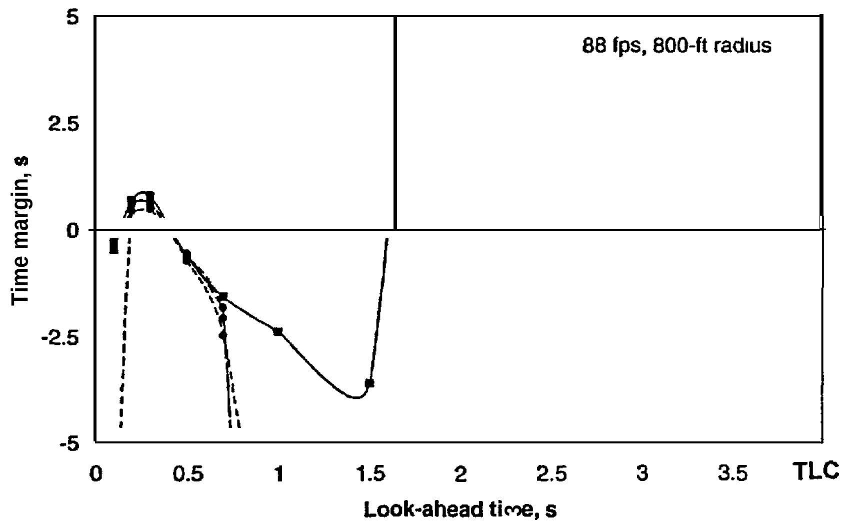


Figure 6-5 TIME MARGIN PLOTS (CONTINUED)



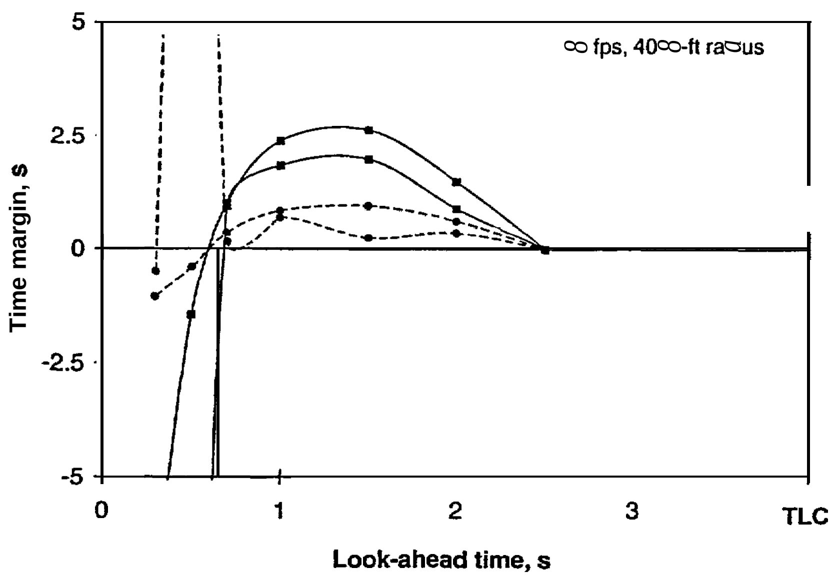


Figure 6-5 TIME MARGIN PLOTS (CONTINUED)

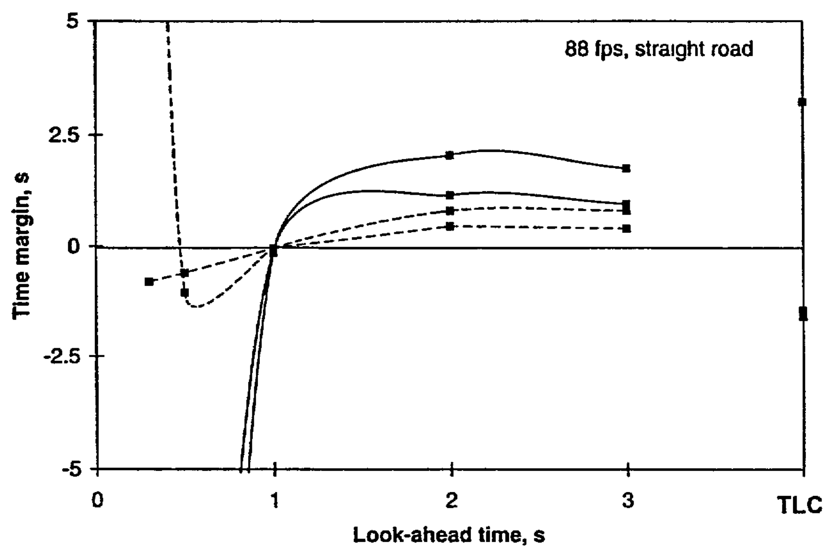


Figure 6-5 **TIME MARGIN PLOTS (CONCLUDED)**

The figure for 88 fps on the same curve looks quite different. The time margins are all positive over a narrow range of look-ahead time--at about 0.5 s. The TLC time margins are positive and relatively high for this case, so TLC would potentially have better performance than TTD in this case. At 66 fps in this curve, there is no look-ahead time where the time margin is positive for all four departure trajectories. This does not mean that the TTD system cannot work under this condition, only that an occasional false alarm or minor lane departure will have to be tolerated unless there are further improvements in the system.

For each speed, there is a look-ahead distance at which TTD time margin has a maximum. Figure 6-6 shows the best look-ahead distance as a function of vehicle speed on the 1000-ft curve. Similarly Figure 6-7 shows the best look-ahead distance as a function of road curvature for a vehicle traveling at 88 fps. A TTD system might perform best if it adapts both its look-ahead distance and warning threshold to the prevailing conditions.

6.2 Propensity for False Alarms

The paths used for "normal" driving in the Section 6.1.1 were generated by the RORSIM driver model. The preliminary selection of warning thresholds was based on those paths. As a validity check, the countermeasure systems' propensity for false alarms was also gauged by calculating the TTD and TLC functions for paths followed by a human driver on an actual freeway. In the case discussed below, the driver was attentive throughout the measurement and never in danger of suffering roadway departure crash.

The plan view of the freeway segment is shown in Figure 6-8; it is an S-curve. A human drove through this segment at 80 fps (55 mph), and instruments in the vehicle recorded the lateral lane position of the vehicle as a function of time. With special settings in the RORSIM model, the RORSJM vehicle was made to follow the human's path through an identical road segment as closely as possible. The instantaneous road curvature is in Figure 6-9a, and the lateral position of the RORSIM vehicle's center of gravity is in Figure 6-9b. The TTD function (for l-s look-ahead time) as calculated by the RORSIM look-ahead countermeasure system is plotted in Figure 6-10a. The lowest value of TTD for this normal driver was 1.5 s. This is slightly higher than the 1.2 s minimum observed for the RORSIM driver, presumably because the human stayed close to the lane center and did not "cut" the curve, as did the RORSIM driver. The lowest values of TLC occurred at places where the road curvature suddenly changed and the TLC algorithm is less accurate. Because these sudden curvature changes are due to the way the road curvature was measured and transferred to RORSIM rather than to its design, the TLC anomalies can be ignored. The lowest TLC at a representative road segment was 1.9 s. This is quite close to the minimum TLC observed for the RORSIM driver of 2.0 s, as noted in Table 6-2. While not being conclusive, this simple experiment increases our confidence that the RORSIM driver model is typical of a human driving behavior. Also, the warning thresholds (1.2 s for TTD 0.8 s for TLC) selected for the studies of effectiveness in that follow should have acceptably low false alarm rates.

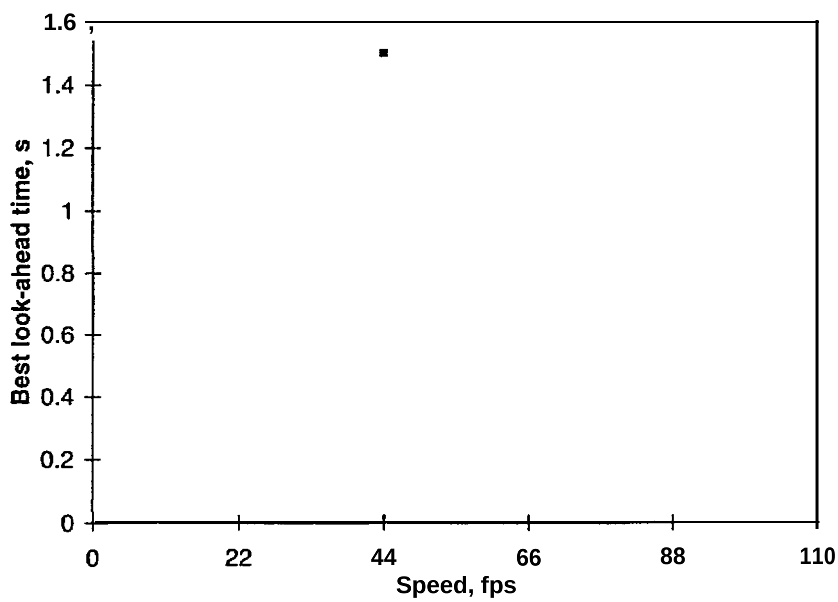


Figure 6-6 SELECTED TTD LOOK-AHEAD TIME VERSUS SPEED, BASED ON THE TIME MARGIN ANALYSIS

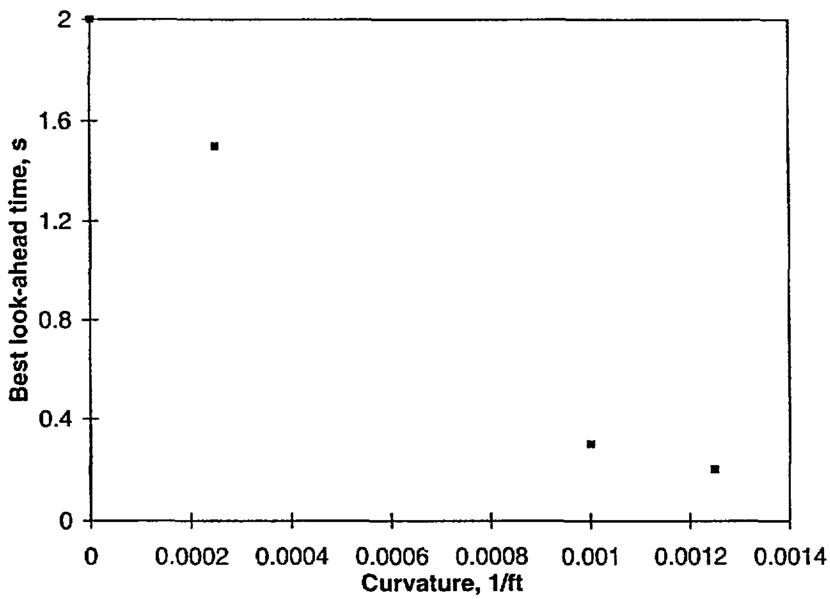


Figure 6-7 SELECTED TTD LOOK-AHEAD TIME VERSUS ROAD CURVATURE, BASED ON THE TIME MARGIN ANALYSIS

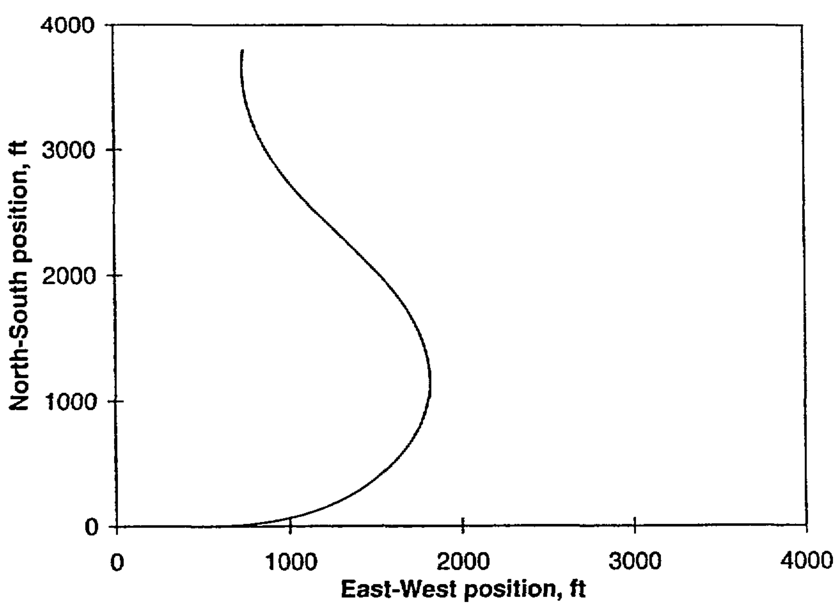


Figure 6-8 PLAN VIEW OF THE FREEWAY SEGMENT FOLLOWED BY THE HUMAN DRIVER

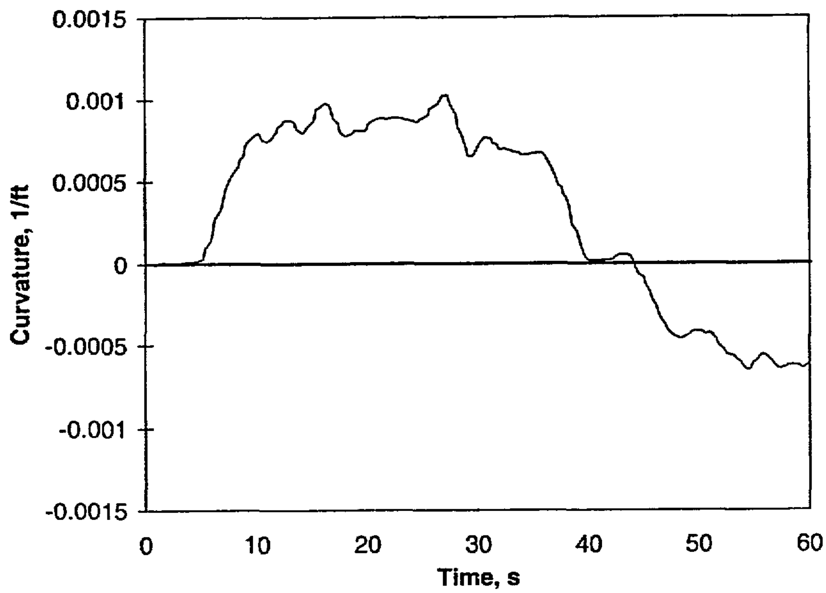


Figure 6-9a. **INSTANTANEOUS CURVATURE OF THE ROAD SEGMENT**

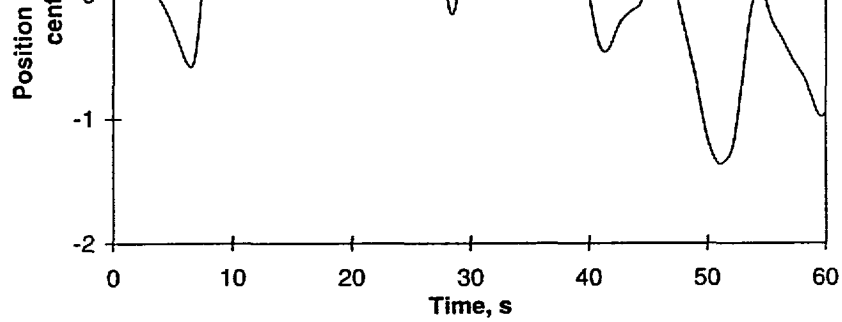


Figure 6-9b **LATERAL POSITION OF THE RORSIM VEHICLE CENTER OF GRAVITY AS IT FOLLOWED THE HUMAN DRIVER'S PATH**

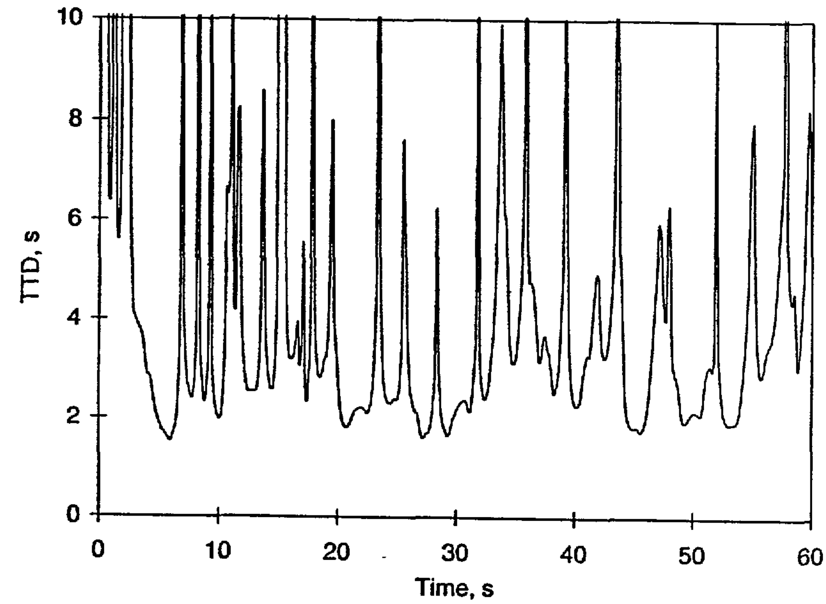


Figure 6-10a TTD FUNCTION OF THE HUMAN DRIVER ON THE FREEWAY S-CURVE AT 88 FPS (60 MPH)

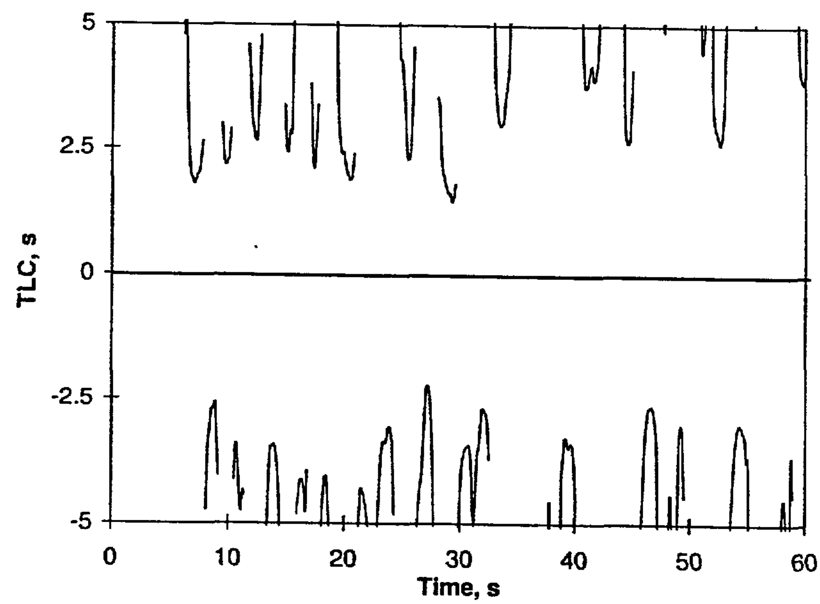


Figure 6-10b TLC FUNCTION OF THE HUMAN DRIVER ON THE FREEWAY S-CURVE AT 88 FPS (60 MPH)

6.3 Effectiveness Estimates

The value of a countermeasure system is judged by its effectiveness in reducing the rate of run-off-road crashes. The potential effectiveness of the two proposed countermeasure systems was estimated by comparing their performance to that of an existing countermeasure system for which actual effectiveness data are available.

The Sonic Nap Alert Pattern (SNAP) was developed and implemented by the Pennsylvania Turnpike Commission [Wood, 1994]. It consists of a series of grooves cut into the shoulder of the turnpike, about 3 inches outside the white edge line. If an inattentive (or napping) driver drifts outside the lane, the grooves make a loud (80 dB in a sedan at 60 mph) sound, which quickly restores the driver's attention. SNAP was initially deployed in 3 1 miles of roadway where the incidence of ROR crashes was relatively high--O.51 per month. During a trial period of 1 to 3 years, the ROR crash rate was only 0.16 per month. SNAP helped reduce the ROR rate by 70 percent. Comments from drivers have been favorable, and the pattern is being deployed along the entire Turnpike. Other states and authorities are adopting variations of the idea as well.

The relative effectiveness of the systems was compared by applying each system to a test suite of 24 potential run-off-road situations. (There were six speed/curvature combinations and four potential crash trajectories for each combination. The ability of the systems to help three classes of drivers (normal, slowly-reacting, and incapacitated) keep a vehicle in or near its own lane was determined. The exact conditions of the simulations for the effectiveness estimate, which are listed in Table 6-l are:

Road Curvature and Speed Combinations: Roadways developed for the time margin studies were used again for the effectiveness studies. The curved road segments consisted of a straight section followed by an entry spiral and an infinitely long section of fixed curvature. The lOOO-ft-radius curve was tested at 44, 66, and 88 fps; all road segments were tested at 88 fps.

Simulation Scenarios: Four potential crash trajectories were generated from each roadway and speed combination by rendering the driver inattentive at different points along the "normal" path. This method was illustrated in Figure 5-l 3.

Driver Type Three classes of driver, based on steering reaction times, were considered. The normal driver has the 50th percentile (median) steering reaction time of 0.82 s. The slowly-reacting driver has the 90th percentile steering reaction time of 1.13 s. The reaction times are from Figure 5-4. A third driver type, who does not react at all to a warning, was also considered. The incapacitated drivers were used to test the active intervention feature of the two electronic countermeasure systems.

Countermeasure Svstems: Three countermeasure systems were considered: forward-looking vision sensor with the Time to Trajectory Divergency (TTD) algorithm, downward-looking vision sensor with the Time to Line Crossing (TLC) algorithm, and the Sonic Nap Alert Pattern (SNAP). The warning thresholds for the two sensor-based systems, which are listed in Table 6-3, were selected from the analysis in Section 6.1. SNAP was modeled in RORSIM as a variation of the downward-looking countermeasure system where a warning is issued when the outside front tire crosses an imaginary line 3 inches beyond the edge line. (While the real SNAP is only on the shoulder, the RORSIM SNAP is on both sides of the vehicle's lane.)

A simulation consists of a vehicle beginning to traverse a road segment at a specified velocity, following the path of the normal, attentive RORSIM driver. The driver becomes inattentive at the predetermined moment and eventually begins to head towards the edge of the lane. The countermeasure system warns the driver, who, after the reaction time, resumes steering control and tries to bring the vehicle back to its proper position in the lane. In the cases where intervention was modeled for the electronic systems, the warning was forgone, and steering control was resumed, without a reaction delay, when the intervention threshold was crossed.

Although the previous steps of analysis required examining several functions as a situation evolved, the result of each simulation is now a single number. The maximum front tire deviation (either to the left or to the right) is the basis for judging the success of a simulation. If a system can warn a driver so that the maximum front tire position in the recovery maneuver is 5.5 ft from the lane center and the lane is 12 ft wide, the simulation was completely successful, since the tire never crossed the lane boundary. If the maximum front tire position in a simulation is 6.5 ft, success is qualified, but the outcome is certainly more desirable than a simulation where an unwarned inattentive driver led the tire to a maximum of 10 or more ft. The overall effectiveness of a system is judged by the distribution of maximum tire positions in the 24 situations in which the system was simulated. The following figures show that the sensor-based systems are potentially more effective than SNAP because they keep vehicles, on average, closer to the travel lane than SNAP. Because SNAP has been shown to reduce the Run-Off-Road crash rate on the Pennsylvania Turnpike, the forward- and downward-looking systems are demonstrated to be effective, within the limits of this study.

Figure 6-l 1 shows the cumulative distribution of maximum front tire deviations for the case of a driver with a 50th percentile steering reaction time. The curve marked with triangles represents the performance of SNAP. Since the lane marker is 6 ft from the lane center, and the SNAP grooves are outside the lane marker, none of the SNAP simulations had a recovery within 6 ft: the driver is not warned until a lane departure has occurred. All of the drivers alerted by SNAP maintained both front tires within 9 ft of the lane center (3 ft of the lane edge). The distribution for TTD is represented by the line with square markers. Drivers assisted by TTD recovered and kept the tire 1 ft away from the edge line in 30 percent of the cases. (Recall that the thresholds were chosen for each speed to avoid alarms during "normal" driving, as defined by the RORSIM driver.) More than 75 percent of the drivers assisted by TTD were able to keep both front tires within the 12-ft lane. The curve marked with circles represents the performance of drivers assisted by TLC. Since the TTD and TLC curves are well above the SNAP curve across the figure, the TTD and TLC algorithms are potentially considerably more effective than SNAP in preventing run-off-road crashes.

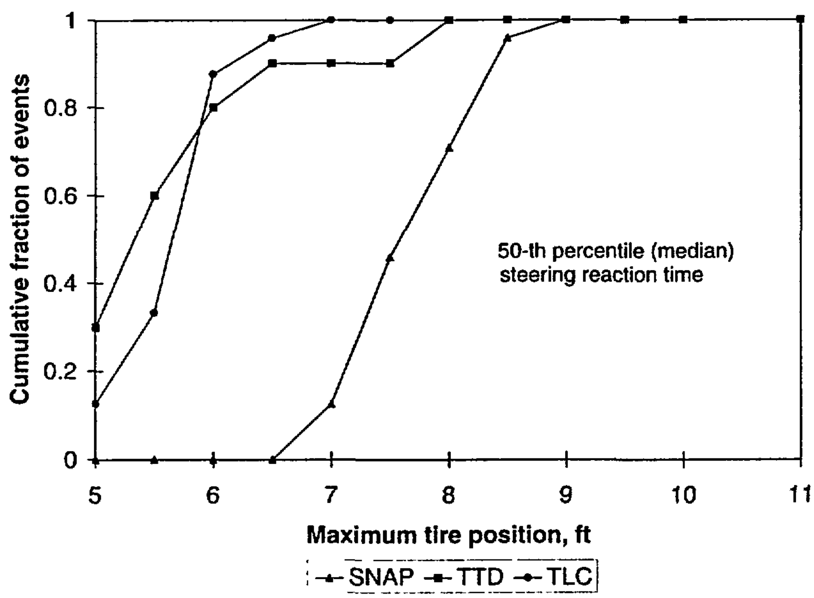


Figure 6-11 CUMULATIVE DISTRIBUTION OF MAXIMUM TIRE POSITIONS IN THE PARAMETER STUDIES, 50TH PERCENTILE STEERING REACTION TIME

Figure 6-12 shows the corresponding distributions for slower-reacting drivers, (i.e., those at the 90th percentile). As expected, the curves are to the right of the curves for the 50th percentile drivers, but the trends are generally the same.

The forward-looking countermeasure system under development at Carnegie Mellon University has an optional feature to prevent warnings when an aggressive driver cuts to the inside of a curve. The feature suppresses a warning when the countermeasure system desires an arc curving in the same direction that the vehicle is turning, and when the vehicle is turning more sharply than the countermeasure desires. The expectation is that the system will desire a curvature in the opposite direction, back toward the road, before the vehicle is in danger. The above cases were repeated with the curve cutting suppression in place. The results for the 50th percentile driver are shown in Figure 6-13, along with the SNAP and TTD without suppression for reference. The modified TTD holds 88 percent of the vehicles successfully within 1.5 ft the lane.

To estimate the effectiveness of the TTD and TLC systems as triggers for active intervention in steering, a set of cases was simulated where the steering reaction time was set to zero, but the threshold was lowered to the point where action was immediately required. The results are plotted in Figure 6-14. The SNAP reference in this figure is for the 90th percentile driver. Since the curves for the active systems are in all cases above the curve for SNAP, properly implemented intervention systems based on these warning algorithms, can be expected to be more effective than SNAP.

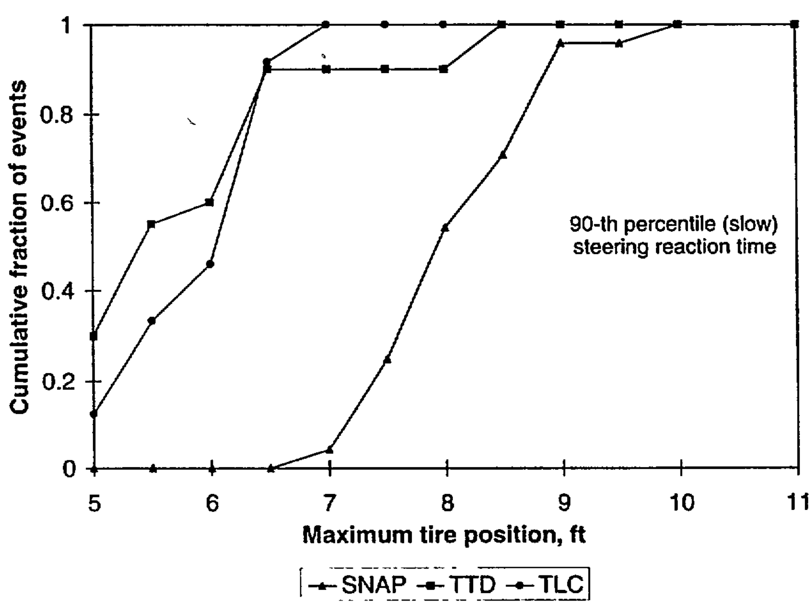


Figure 6-12 CUMULATIVE DISTRIBUTION OF MAXIMUM TIRE POSITIONS IN THE PARAMETER STUDIES, 90TH PERCENTILE STEERING REACTION TIME

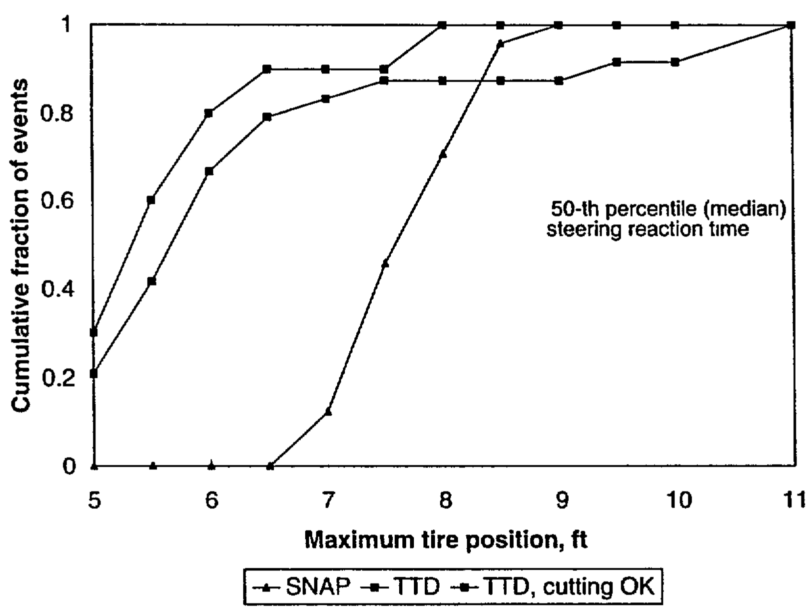


Figure 6-13 CUMULATIVE DISTRIBUTION OF TIRE POSITIONS, FORWARD-LOOKING SYSTEM WITH AND WITHOUT CURVE-CUTTING LOGIC, 50TH PERCENTILE STEERING REACTION TIME

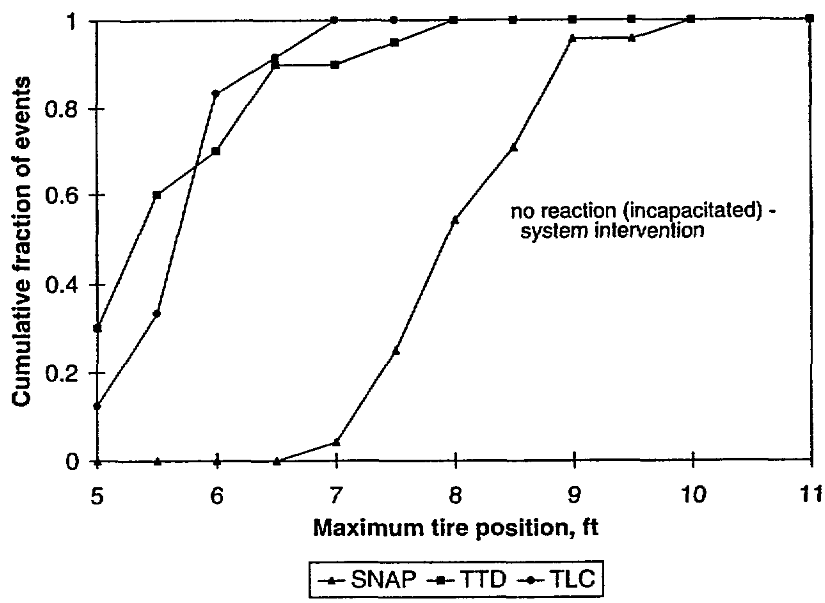


Figure 6-14 CUMULATIVE DISTRIBUTION OF MAXIMUM TIRE POSITIONS, ELECTRONIC SYSTEMS WITH ACTIVE INTERVENTION

A quantitative, albiet rough, estimate of the electronic countermeasures' effectiveness can be made by comparing the above data with the 70 percent effectiveness observed during the trial period of SNAP [Wood, 1994]. The maximum lane position within which SNAP held 70 of the vehicles was 8 ft for the median drivers (in Figure 6-11) and 8.5 ft for the slowly-reacting drivers (in Figure 6-12). All of the drivers assisted by either electronic countermeasure system recovered before the front tire was 8 or 8.5 ft from the lane center. In other words, the parameter studies cannot resolve the difference between the systems' effectiveness and 100 percent effectiveness. Of course, the scenario considered (an inattentive driver drifting out of the lane) is but a part of the overall Run-Off-Road problem, and the systems will not actually be completely effective even for this scenario. Information necessary to make a better quantitative estimate the effectiveness (such as details of the crashes SNAP did not prevent) are not presently available. However, this limited study shows that the electronic countermeasure systems are potentially quite effective.

The SNAP data represents effectiveness on roads with wide (12-ft) paved shoulders, and its effectiveness on roads with narrower shoulders would no doubt be lower. The effectiveness advantage of the electronic countermeasures over SNAP is likely to increase on roads with narrower shoulders, since the earlier warning provided by the electronic countermeasures will be more significant when there is less time between the moment of lane departure and the crash. However, this effect may be offset by the difference in availability between SNAP and the electronic countermeasures. Once deployed, SNAP is always functional; it applies to nearly all vehicles, and the grooves make their noise even when they are filled with ice or snow. On the other hand, the performance of the electronic countermeasures may be degraded due to environmental conditions, adverse sun angle, or other factors. The relative importance of these additional performance factors cannot be determined from the modeling efforts conducted for this Task, and deserves further investigation.

6.4 Summary: Viability and Feasibility of a Lateral Countermeasure System

RORSIM, a computer model for simulating vehicle dynamics and countermeasure systems has been developed and exercised to demonstrate the potential utility of lateral countermeasure systems. It was used to compare the effectiveness of similar systems under identical conditions, to duplicate conditions produced by human drivers, to generate data for detailed analysis, and to provide guidance for developing performance specifications. RORSIM can simulate a much broader range of Run-Off-Road situations than have been analyzed in this project. It is flexible enough that more countermeasure systems could be easily incorporated, including rear-end and lane change/merge collision avoidance.

The simulations and analysis of the lateral countermeasure systems indicate that in-vehicle sensor and warning systems offer a significantly reduced rate of Run-Off-Road crashes. Two systems have been shown to help maintain vehicles in their lane, or at least closer to their lane, than an existing system (SNAP), which has proven to reduce the run-off-road accident rate.

The forward-looking system can keep a large fraction of departure-bound vehicles in the lane of travel. The TTD algorithm has the advantage that one of its internal calculations is an optimal or desired turning radius, which can be used for automatic steering if necessary.

The downward-looking system also proved to be significantly more effective in keeping vehicles on or near the travel lane than the standard system (SNAP). The variance of maximum lane position of simulated vehicles equipped with the downward-looking system was less than for the forward-looking system, for the cases studied. A large fraction of the vehicles with the forward-looking system recovered at or near the edge lane, rather than 1 ft inside or (worse) 1 ft outside. TLC, as implemented in RORSIM, requires but a single sensor, though it does need a measurement of lane width to work properly on both sides of the lane. A disadvantage of the RORSIM TIC algorithm is that the input signal must be twice differentiated, so it is susceptible to noise unless it is improved.

7.0 Results: Longitudinal Countermeasure System Study

The purpose of the longitudinal countermeasure system is to ensure that the vehicle is operating at a safe speed, particularity on curved sections of roadway. Excessive speed accounted for 32 percent of the crashes in the Task 1 clinical study. Based on these and other findings of Task 1, the project team determined in Task 2 that a countermeasure with the broad functional goal of slowing the vehicle so that it enters a curve at a safe speed could be effective in reducing run-off-road crashes. The countermeasure system notes that the vehicle is approaching a curve at a certain distance ahead, estimates the maximum safe speed for negotiating the curve, and if necessary, suggests that the driver decelerate the vehicle. A system with active intervention capabilities may apply the brakes. Therefore, the longitudinal countermeasure systems studied in this phase could be characterized as curve warning systems.

The first step in the analysis is to elucidate the equation that governs the deceleration of a vehicle approaching a curve. Then the procedure for estimating the maximum safe speed for a curve is discussed. The crucial part of the analysis is the investigation of the effects of various countermeasure errors on the speed at which a vehicle enters a curve. This methodology formed the basis for the preliminary specifications on the measurement accuracy necessary for an effective longitudinal countermeasure system.

The following analysis is based on the understanding that the countermeasure system is for safety and not for enforcement. For example, curves in two-lane rural highways and freeway ramps are frequently marked with a recommended safe speed. A passenger car can typically negotiate a curve with dry pavement faster than the posted speed. A countermeasure system for enforcement would warn the driver or perhaps intervene if the driver attempted to enter the curve faster than the posted speed. Drivers would be annoyed by a system that forced them to drive through a curve significantly slower than they “know” they safely could. On the other hand, a system that permits vehicles to drive at or near the limits of safety could cause a roadway departure when the safety margin is only slightly less than believed.

7.1 Warning Distance and Time Requirements

The permissible speed for a vehicle approaching a curve is calculated using basic kinematics:

$$V^2 = V_c^2 + 2ad \qquad \textbf{(7-1)}$$

where

V = the maximum permissible speed at distance d from the curve entry
V_c = the maximum safe speed of the curve
a = the assumed constant deceleration to reach the curve, and
d = the distance between the current vehicle position and the curve entry.

For a comfortable, natural approach to a curve, the deceleration, a, may have a value of 0.2 g or 6.4 ft/s^2. If a system provides for intervention, it might begin braking when the required deceleration is near the limit of a vehicle, say, 0.6 g or 19.3 ft/s^2. The maximum speeds for these two deceleration rates are plotted in Figure 7- 1. A longitudinal countermeasure system would continuously compare the vehicle's current speed to the maximum permissible speed for an upcoming curve. A warning would be issued when the vehicle's speed is above the lower curve in the figure, and a system with active intervention capabilities would brake the vehicle when the speed is above the upper curve. In practice, the system must allow for a human's finite reaction time, so the warning might begin when the distance to the curve entry is

$$d = \frac{V^2 - V_c^2}{2a} + t_r v \qquad (7\text{-}2)$$

where

t_r = the reaction time due to countermeasure system and driver reaction delays.

When the vehicle is very close to the curve entry, the system must be forbidden from initiating an action; otherwise, it might issue a warning or apply the brakes for a speed discrepancy of only one or two mph. The difference between the "warn" and "intervene" values of deceleration needs to be large enough that the driver has a chance to react to a warning and begin decelerating the vehicle before the system applies the brakes. Furthermore, the system must not apply braking when a vehicle is in a curve, to avoid reducing already strained steering ability.

The equation above includes the tacit assumption that the desired acceleration can be instantaneously applied. The design of practical system must include the step of verifying that the distance traveled as the deceleration builds is indeed negligible.

7.2 Current Practice for Safety in Curves

The maximum safe speed in a curve depends on the geometry of the roadway, the surface conditions, the skill (or tolerance for discomfort) of the driver, and the rollover stability of the vehicle. The geometric factors of a curve that are always fixed are its radius of curvature and its superelevation or bank. The other road-dependent factor is the maximum side friction factor that can be generated by the road surface. The friction factor can vary from vehicle to vehicle, and from hour to hour; it varies with the temperature of the surface, precipitation on the surface, the tires and speed of the vehicle.

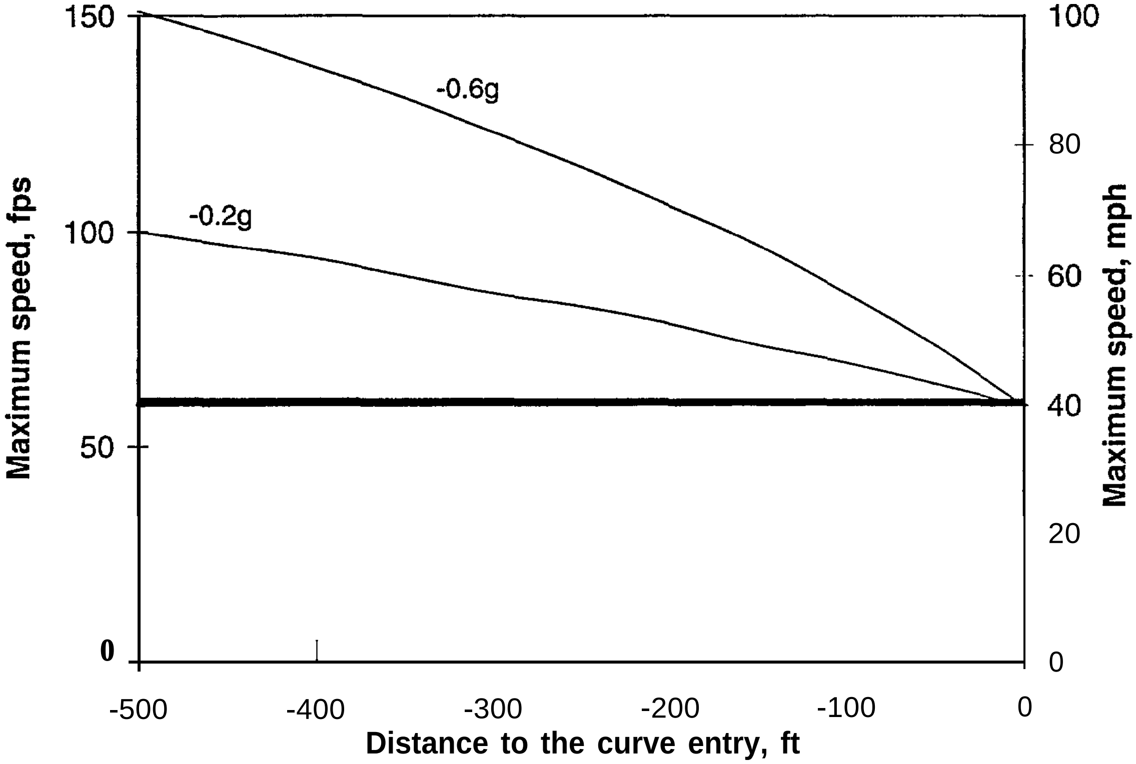


Figure 7-1 MAXIMUM PERMISSIBLE SPEEDS ON APPROACH TO A CURVE OF 60 FPS (41 MPH), ASSUMING FIXED DECELERATION RATES

The formula for the maximum safe design speed of a curve is [AASHTO 1994, p. 141]

$$V_c = \sqrt{gR\frac{e+f}{1-ef}} \quad . \tag{7-3}$$

where

V_c = the maximum safe speed in a curve
g = the gravitational acceleration constant
R = the radius of the curve
e = the superelevation of the curve
f = the side friction factor of the pavement and tires

This full formula can be derived from the force balance of a mass on a banked segment of a constant-radius curve. A simpler version of this formula is usually used for design calculations, but the following analysis requires the complete formula.

The side friction factor, fin the equations, is the ratio of actual side friction force on an object to the normal force. This ratio must be less than or equal to the quantity commonly called the coefficient of friction, which is the ratio of maximum possible friction force to normal force. The side friction factor assumed for highway design (as opposed to highway use) is generally less than 0.1 or 0.2. Under most conditions, a road surface can provide a significantly higher side friction factor, and aggressive motorists routinely drive curves much faster than the design speed. The low value is used for design to allow for the possibility of ice on the surface. Even if the road is capable of providing a higher side friction factor, persons in the vehicle may experience the discomfort associated with high side forces, and a vehicle with a high center of gravity may be subject to roll over. The maximum safe side force should be fixed for a given vehicle, though it might vary with the manner by which the vehicle is loaded or maneuvered. The desired maximum side force could be an adjustable parameter set to the driver's preference. It could vary from one driver to the next, but it would probably be established before a trip. The maximum side force selected by the driver would be an upper limit; the actual force permitted by the countermeasure for curve negotiation might be further limited by its estimate of the available side friction and roll over stability of the vehicle.

When the value off is the maximum friction available, Equation 3 represents the speed at which it would just barely be possible to negotiate the curve without loosing control, neglecting dynamic considerations. The countermeasure must not use this absolute maximum speed when calculating whether to trigger a warning, since measurement errors and variability in driver skill (reaction time, deceleration rate, steering vagaries) could mean that the true safe speed is somewhat lower. Instead, there should be a speed cushion (i.e., the speed at which the countermeasure permits the vehicle to enter the curve should be somewhat lower than its estimate of the maximum speed at which the curve could possibly be negotiated). The cushion or margin, of course, should not be too large, or the driver would perceive that the system generates too many false alarms. The effect on the speed cushion of incorrect measurements or assumptions on the part of the countermeasure system is the next subject of discussion.

7.3 Measurement Sensitivity Analysis

A vehicle may enter a curve at a speed higher than desired for reasons that fall in two broad categories: the driver may not have noticed the curve, or the driver may have misjudged the maximum safe speed for the curve. A countermeasure system will help the driver avoid these mistakes, but it, too, is subject to measurement error. We, assume that the countermeasure system will be aware of the presence of a curve, but it may misjudge the distance to the curve entry, the safe speed for negotiating the curve, or the driver's ability to maneuver as expected.

The system will miscalculate the proper speed to enter the curve if the radius, superelevation, or friction coefficient is measured incorrectly. These variables will influence the safe speed estimate through the relationship in Equation 7-3. Even if the proper speed is calculated, the vehicle may not enter the curve at the desired speed. The entry speed might be too high if the distance to the curve or one of the other variables in Equation 7-2 is incorrect. In Equations (7-2) and (7-3), there are a total of eight parameters that can influence the speed at which the vehicle enters a curve. They are:

- radius of the curve
- superelevation of the road in the curve
- available side friction force
- distance from the vehicle to the curve entry
- current speed of the vehicle
- driver steering performance
- driver reaction time
- deceleration rate.

The effects on countermeasure performance of each of these miscalculations will be analyzed separately.

For the purpose of plotting trends in the following analysis, a speed error of 10 percent is assumed to be tolerable. If a system is designed where the combined errors of all parameters cannot control the entry speed this well, the speed cushion will have to be adjusted accordingly.

7.3.1 Error in Radius of Curvature

The countermeasure system's estimate of the safe speed for an upcoming curve depends in part on its measurement of the radius of curvature. A smaller radius corresponds to a sharper curve and a slower safe speed.

The error (V_{err_R}) in the estimate of the maximum safe speed for a curve due to an error of R_{err} in the radius measurement depends on the partial derivative of V_c with respect to R through Equation 7-3:

$$V_{err\_R} = \frac{\partial V_c}{\partial R} R_{err} \tag{7-4}$$

The fractional error in safe speed measurement due to an error in radius measurement is

$$\begin{aligned} \frac{V_{err\_R}}{V_c} &= \frac{\frac{\partial V_c}{\partial R} R_{err}}{V_c} \\ &= \frac{\frac{1}{2}\sqrt{\frac{g}{R}}\sqrt{\frac{e+f}{1-ef}}\, R_{err}}{\sqrt{gR\frac{e+f}{1-ef}}} \\ &= \frac{1}{2R} R_{err} \end{aligned} \tag{7-5}$$

The sensitivity to error in radius measurement depends on the actual value of the radius, but not on the actual values of the superelevation or side friction. If we define a "tolerable" error in safe speed measurement to be, say, 10 percent, then the tolerable error in radius measurement, R_{err}, can be expressed as a function of the actual radius R.

$$\frac{V_{err\_R}}{V_c} = 0.1$$

$$R_{err} = 2R(0.1) = 0.2R \quad . \tag{7-6}$$

This equation is plotted in Figure 7-2. For example, if the actual radius is 1000 ft, the error in maximum safe speed estimate will be less than 10 percent of the actual safe speed if the error in radius measurement is 200 ft. In other words, the radius must be known to an accuracy of 20 percent to provide a safe speed estimate with an accuracy of 10 percent. However, as will be discussed in Section 7.3.6, human driving practices will affect the effective minimum radius.

7.3.2 Error in Superelevation

Of the physical and geometrical properties of a curve, the superelevation is the one over which the driver has the least control. Through steering, a driver can effect subtle but quite significant changes in the minimum radius of curvature. The side friction force demanded of the road depends on the speed and steering, but the cross slope built into the highway is constant.

Following the same procedure as for the analysis of errors in radius measurement, the effects of errors in superelevation measurement are analyzed by taking the partial derivative of the speed function (Equation 7-3) with respect to the superelevation:

$$V_{err\_e} = \frac{\partial V_c}{\partial e} e_{err}$$

$$= \frac{1}{2}\sqrt{gR}\left(\frac{1}{\sqrt{e+f}\sqrt{1-ef}} + \frac{\sqrt{e+f}}{(1-ef)^{\frac{3}{2}}}f\right)e_{err} \quad . \tag{7-7}$$

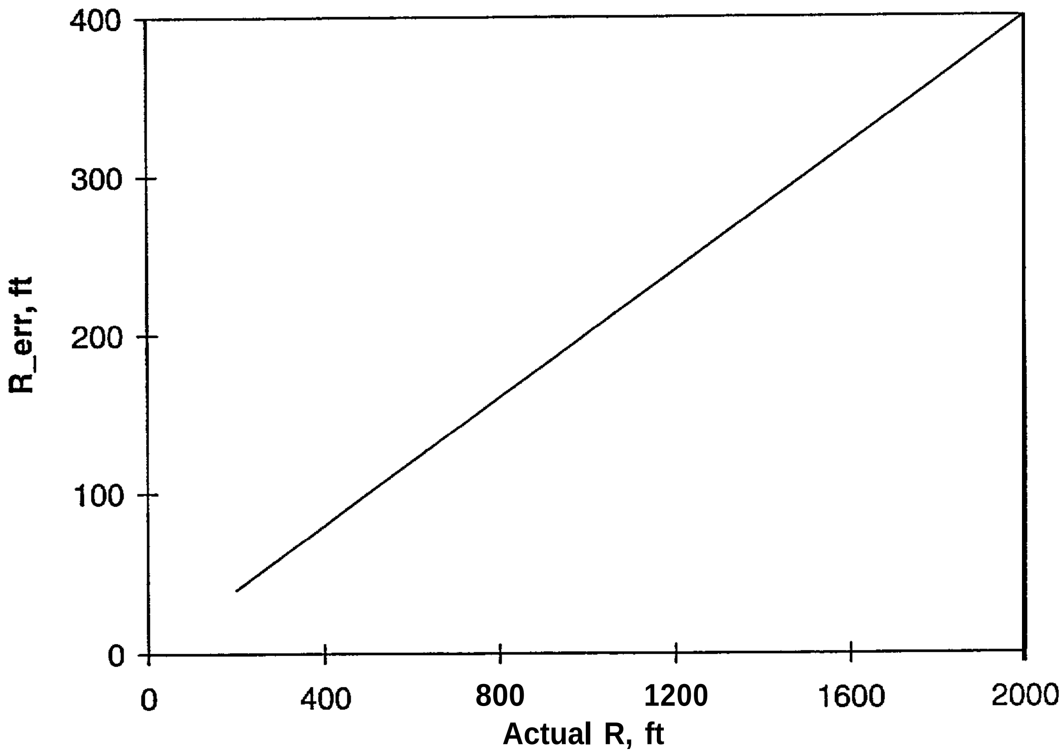


Figure 7-2 ABSOLUTE ERROR IN MEASUREMENT OF THE RADIUS OF A CURVE THAT YIELDS A "TOLERABLE" 10-PERCENT ERROR IN THE ESTIMATED MAXIMUM SAFE SPEED OF THE CURVE

The fractional error in safe speed estimate, due to an error in superelevation measurement, is

$$\frac{V_{err\_e}}{V_c} = \frac{1}{2}\,\frac{1+f^2}{(1-ef)(e+f)} \tag{7-8}$$

The error depends on the actual values of the superelevation and side friction factor, but not on the actual value of the radius. This superelevation measurement error that corresponds to a "tolerable" 10 percent error in safe speed measurement is plotted in Figure 7-3. Whereas the ratio in Equation 7-5 depends on the actual value of only a single quantity, R, the ratio in Equation 7-8 depends on the actual values of two parameters (i.e., e and f). The contour plot and surface plot in Figure 7-3 show the same relationship in two formats.

Note that common highway design admits a maximum superelevation of 12 percent, and that only rarely (AASHTO 1994, p. 151). Therefore, if any curve were assumed to have a superelevation of 6 percent, the maximum conceivable error (aside from the possibility of adverse superelevation) would be 6 percent. In Figure 7-3, an error in superelevation estimate of 6 percent (0.06) is "tolerable" when the actual friction is above about 0.3 (at no superelevation) or 0.2 (at 12 percent superelevation). The friction is above these values in most surface conditions. Furthermore, the safe speed estimate is more sensitive to superelevation error at higher actual superelevations, when the fixed value of 6 percent is conservative. Therefore, measurement precision of superelevation is not a major issue. Because error due to superelevation inaccuracy will combine with other errors, however, a rough estimate of superelevation might be advisable.

7.3.3 Error in Side Friction Factor

Neither a countermeasure system nor a reasonable driver would attempt to negotiate a curve at a speed requiring the very maximum available side friction force. Both a system and a human use an estimated side friction capability (with a safety factor) in determining what speed to use. The following analysis determines how an error in the estimated side friction capability of a curved roadway segment might affect the planned speed for the segment.

The equations for the analysis of error in side friction factor measurement have a form quite similar to those for error in superelevation.

$$
\begin{aligned}
V_{err\_f} &= \frac{\partial V_c}{\partial f} f_{err} \\
&= \frac{1}{2}\sqrt{gR}\left(\frac{1}{\sqrt{e+f}\sqrt{1-ef}} + \frac{\sqrt{e+f}}{(1-ef)^{\frac{3}{2}}} e \right) f_{err} \ .
\end{aligned}
\qquad (7\text{-}9)
$$

The fractional error in safe speed estimate, due to an error in measurement of the available side friction, is

$$
\frac{V_{err\_f}}{V_c} = \frac{1}{2} \frac{1+e^2}{(1-ef)(e+f)} f_{err} \ . \qquad (7\text{-}10)
$$

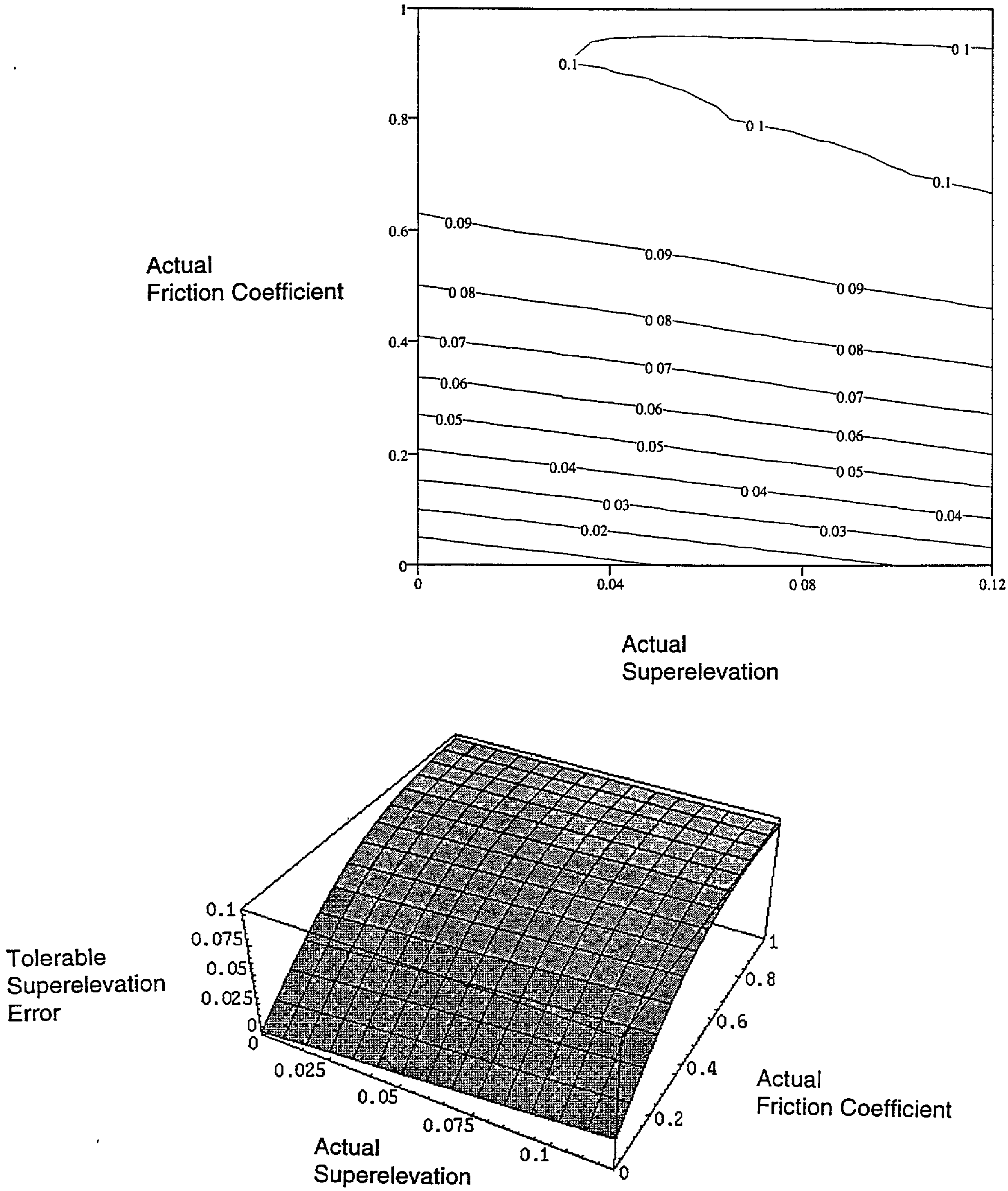


Figure 7-3 ABSOLUTE ERROR IN MEASUREMENT OF THE SUPERELEVATION OF A CURVE THAT YIELDS A "TOLERABLE" 10-PERCENT ERROR IN THE ESTIMATED MAXIMUM SAFE SPEED OF THE CURVE. THIS IS SHOWN AS A FUNCTION OF THE ACTUAL SIDE FRICTION COEFFICIENT AND THE ACTUAL SUPERELEVATION OF THE CURVE. THE SAME RELATION IS SHOWN AS BOTH A CONTOUR PLOT AND A SURFACE PLOT.

The error depends on the actual values of the superelevation and side friction factor, but not on the actual value of the radius. The error in measurement of available side friction that corresponds to a "tolerable" 10 percent error in safe speed estimate is plotted in Figure 7-4. The tolerable error depends only slightly on the actual superelevation, since it is primarily a function of the actual friction. As might have been expected, the friction must be known most precisely when the actual value is quite low; when the when friction is high, its value need not be known as precisely.

Ray [1995] has shown through simulations that the coefficient of friction can be determined in real time using sensors that could reasonably be mounted on a vehicle. Under most conditions, if the vehicle is maneuvering, the coefficient of friction can be estimated to +/- 0.05 of the actual value. Briefly, the procedure is to measure tire angles and vehicle accelerations and use a simplified vehicle model to infer the tire forces. Then the most likely coefficient of friction is estimated. Of course, this estimate is of the friction coefficient at the tires' current location, and it is not necessarily a precise indicator of the friction in upcoming road segments. According to Figure 7-5, a friction error of 0.05 is "tolerable" for all but the most slippery of conditions (i.e., when the friction coefficient is below about 0.2). Usually, only under conditions of ice or water with shallow tire tread is the friction coefficient below 0.2. Under these conditions, the mere fact that the coefficient of friction is unusually low is sufficient reason for a driver to be advised to exercise extra vigilance. For common surface conditions of dry or modest moisture (friction coefficient above 0.6 or so), a friction estimate within 0.05 would be adequate. Of course, in the case of sudden friction coefficient changes, such as ice patches or oil spills, a friction measurement under the tires' current position is inadequate. To function under these circumstances, a countermeasure system would have to communicate with the infrastructure in some way or perhaps with another vehicle some appropriate distance ahead.

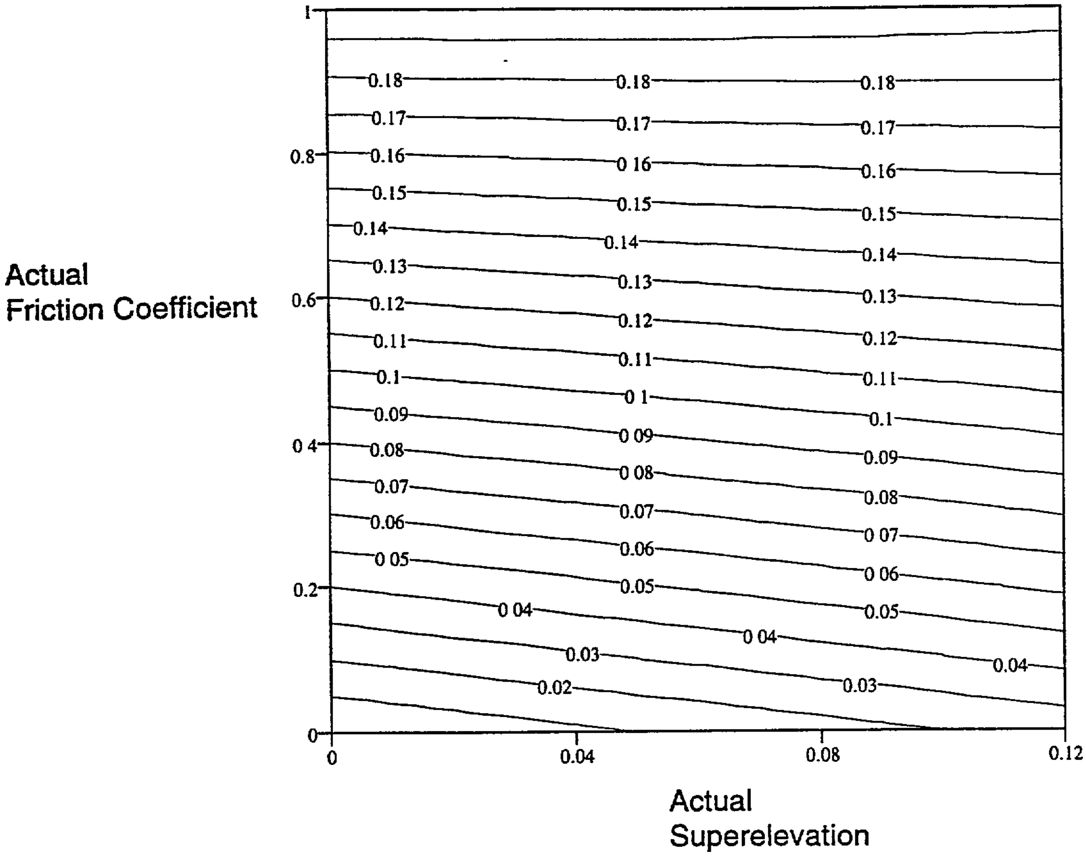
7.3.4 Error in Distance

If the countermeasure system misjudges the distance to the curve entry point, the vehicle might enter the curve too fast, even when the maximum safe speed of the curve has been properly estimated. A position measurement error may be in the vehicle's position or in the location of the curve in the system's database. If there is a constant bias error in position, the vehicle will enter the curve when the system believes it is still a distance d_{err} away, and the speed of the vehicle will be:

$$V_a = \sqrt{V_c^2 + 2ad_{err}} \qquad (7\text{-}11)$$

where

V_a = the actual entry speed
V_c = the desired entry speed
a = the planned constant deceleration
d_{err} = the error in position measurement



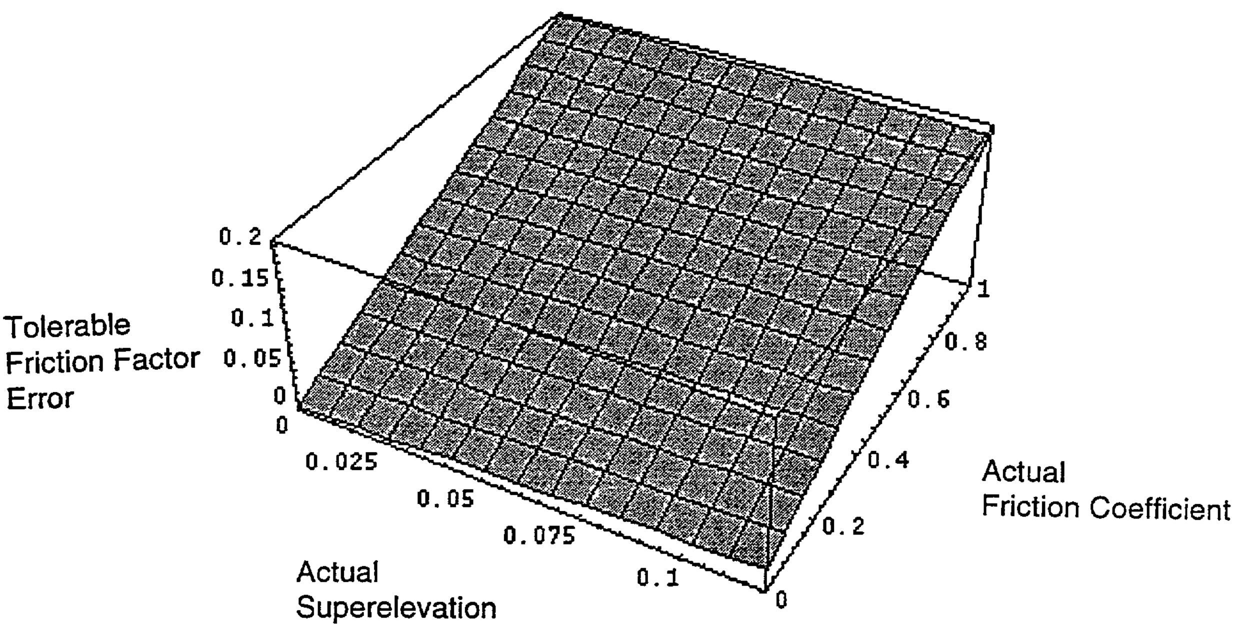


Figure 7-4 ABSOLUTE ERROR IN MEASUREMENT OF THE SIDE FRICTION COEFFICIENT OF A CURVE THAT YIELDS A "TOLERABLE" 10-PERCENT ERROR IN THE ESTIMATED MAXIMUM SAFE SPEED OF THE CURVE. THIS IS SHOWN AS A FUNCTION OF THE ACTUAL SIDE FRICTION COEFFICIENT AND THE ACTUAL SUPERELEVATION OF THE CURVE. THE SAME RELATION IS SHOWN AS BOTH A CONTOUR PLOT AND A SURFACE PLOT

The relative error in speed is

$$\frac{V_a}{V_c} = \frac{\sqrt{V_c^{\,2} + 2ad_{err}}}{V_c} \quad . \tag{7-12}$$

and the "tolerable" error in distance measurement is

$$d_{err} = 0.105 \; \frac{V_c^{\,2}}{a}$$

For a fixed deceleration, the relative error depends only on the desired entry speed. Figure 7-5 shows the distance measurement error that yields a 10 percent error in entry speed for a fixed deceleration of a = 6.4 ft/s^2 (0.2 g). When the actual speed of the curve is less than about 30 mph (44 fps), an error in position of only 40 ft. can lead to a significant entry speed error. Global Positioning System (GPS) may be adequate for advising a driver that a curve lies ahead, when the driver still has time to assess the situation and react accordingly. However, differential correction to the GPS position estimate (and a good map) will be essential if the countermeasure is to provide an accurate and timely warning of excessive speed during the approach to a curve.

7.3.5 Error in Vehicle Speed Measurement

The calculations of required warning time and deceleration rate depend on the current speed of the vehicle. If the speedometer is not calibrated properly, the vehicle may enter the curve too fast even if the curve itself has been properly assessed. If the driver has been apprised of the curve by the countermeasure system, the driver may adjust the speed according to the feel of the vehicle and the curve. Thus a modest speedometer error would be inconsequential. In the case where a countermeasure system continuously monitors the vehicle's speed as it decelerates toward a road segment, an error in vehicle speed measurement would cause an equal error in entry speed.

The effect of an error in vehicle speed measurement at the time when the system decides whether to warn the driver is more subtle. Because vehicle speed occurs as a squared term in Equation 7-2, a speedometer error of only 5 percent at the time when the warning decision is made can lead to a curve entry speed error of approximately 10 percent, if after the warning either the driver or the countermeasure decelerates the vehicle at the assumed, fixed deceleration rate. Automobile speedometers are typically accurate to +/- 4.5 fps (3 mph). At 88 fps (60 mph), this is 5 percent of the true value. The implication, then, is that a simplistic system, selecting a deceleration and then braking without further correction until the curve entry, is probably inadequate. A capable human driver should judge and apply the appropriate braking. An alternative solution would be to use a more accurate means of estimating vehicle velocity, such as GPS. Inexpensive GPS receivers can estimate velocity using doppler shift to an accuracy of better than 1.5 fps (1 mph).

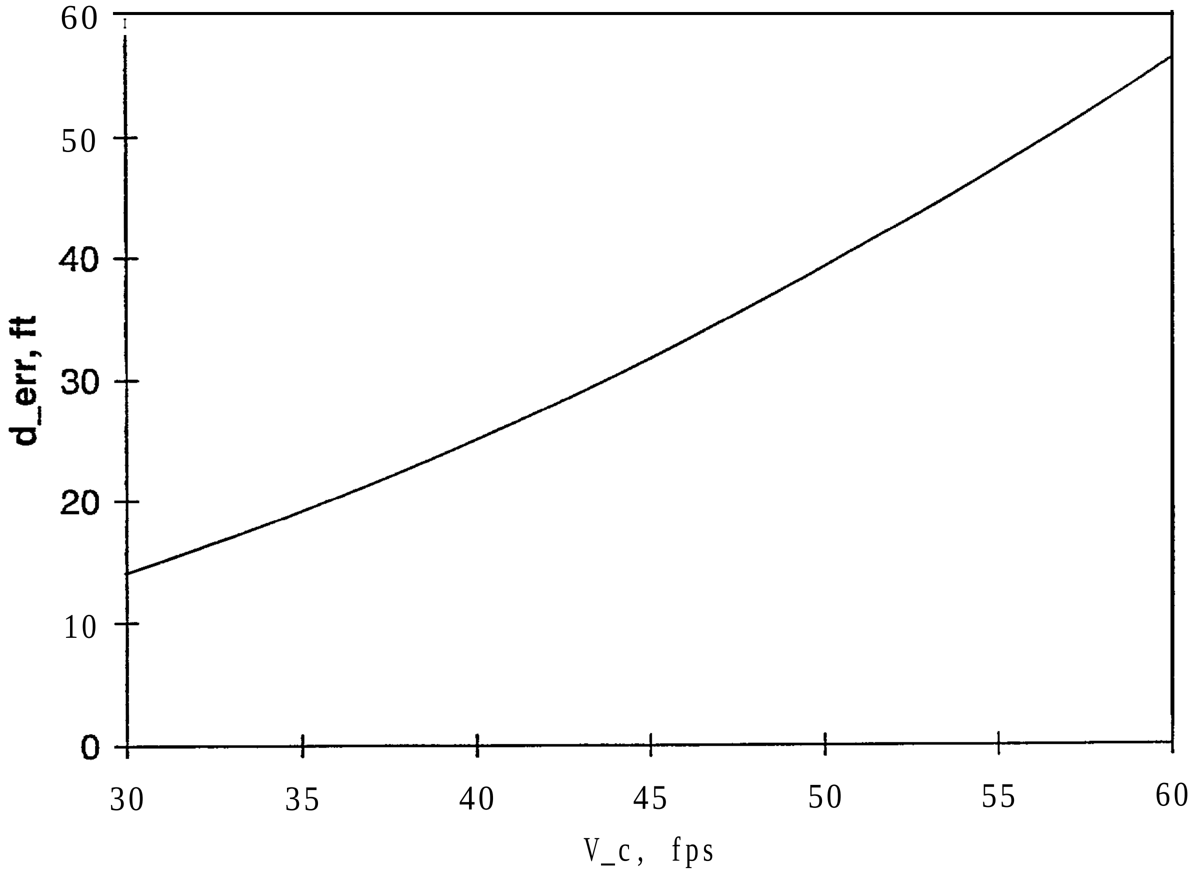


Figure 7-5 ABSOLUTE ERROR IN MEASUREMENT OF DISTANCE-TO-THE-CURVE THAT YIELDS A "TOLERABLE" 10-PERCENT ERROR IN ACTUAL CURVE ENTRY SPEED, ASSUMING CONSTANT DECELERATION AT A FIXED RATE OF 4.4 FT/S^2. THIS IS SHOWN AS A FUNCTION OF ACTUAL CURVE SAFE SPEED

7.3.6 Error in Driver Steering Performance (Actual Minimum Radius)

If the driver exactly follows the lane center throughout the curve, then the analysis of Section 7.3.1 would be sufficient to describe the effect of radius. A skilled, alert driver may not exactly follow the lane centerline in a curve. The driver may "cut" to the inside of a long, high-speed curve to lessen the travel distance, or may move "outside-inside-outside" to increase the effective radius of the curve so it can be driven at a higher speed. An unskilled or modestly inattentive driver might not maintain a constant curvature but meander as in Figure 6-2 (RORSIM driver) or 6-10 (early 30's male driver). In this case, the maximum safe or comfortable speed would be governed by the minimum radius actually driven by the driver. The dynamic effects of load transfer between the left and right tires could play an role, beyond the strictly kinematic considerations, when the curve is tight and the driving is erratic. Therefore, when estimating the radius of curvature, an allowance for driver skill should be made.

7.3.7 Error in Allowed Driver Reaction Time

The countermeasure system must assume a nominal driver reaction time in deciding when to warn the driver. If the driver takes too long to react before beginning to decelerate, the vehicle will travel farther than anticipated at the original speed. The effect will be that the deceleration will need to be more severe than anticipated to slow the vehicle in time, or the curve entry speed will be too fast. Over a reasonable range of curve safe speeds and initial approach speeds, the "tolerable" reaction time error is 0.4 s or more. The difference between the 50-th percentile and 90-th percentile braking reaction times (in response to a surprise) is roughly 0.4 s. Little accuracy would be lost in most circumstances if a conservative choice of the 90-th percentile braking reaction time were assumed. If more accuracy is needed, the reaction time could be combined with the desired deceleration level on a "driver preference" knob, or a more sophisticated system could adapt to the perceived reaction time of the present driver. Also, an alerted driver should be able to compensate for a delayed braking onset.

7.3.8 Error in Assumed Deceleration Rate

The thresholds for a longitudinal countermeasure system will likely be cast in terms of required deceleration rates, because the acceleration is a measure of the urgency of response needed from the driver. When a curve or other reduced-speed road segment lies ahead, the countermeasure system will use Equation 7-2 to determine the deceleration required to slow the vehicle in time. When the required deceleration exceeds a pre-established limit, the warning will be issued. Of course, different drivers have different "normal" practices for slowing down [Wortmann and Matthias 1983]. Some drivers decelerate gently, beginning well ahead of the need, while others maintain their cruising speed as long as possible, slowing down, as it were, at the last second. A warning given when the required acceleration is -0.15 g, comfortable for a conservative driver, might be perceived as too early for an aggressive driver, accustomed to braking at 0.3 g. A longitudinal countermeasure system, therefore, might have an adjustable threshold. The adjustment might be a knob set by the driver to personal preference, or a more sophisticated system could sense the driver's usual braking practice and adjust accordingly.

The eventual curve entry speed is only moderately sensitive to the actual deceleration rate. An alerted driver can apply extra braking if necessary. Difficulties might arise when the pavement is slippery and extra deceleration is not possible, or when an inexperienced driver is faced with the necessity to brake more than usual and then panics. Another possibility is that the driver does not perceive the hazard signaled by the warning and chooses to ignore it. This might occur when there is "black ice" ahead, or when the view of the upcoming curve is occluded. Perhaps the system should specifically advise the driver when it detects a hazard that the driver might not. A voice from the dashboard would say, "Caution! Ice Patches". This would be the electronic equivalent of the familiar "hidden curve" sign.

7.4 Results: Viability and Feasibility of a Longitudinal Countermeasure System

A longitudinal, or speed-monitoring, countermeasure system can be based on much simpler principles than a lateral, or steering, countermeasure system. Modest errors in nearly any of the measured parameters cause only a minor error in the curve entry speed. The combined errors in the eight input parameters could potentially be substantial, so the individual errors should be kept as small as reasonable.

Probably the most critical of the eight factors analyzed is the friction. Sudden, but quite possible, changes in the surface friction can be disastrous. The analysis of Section 7.3.3 showed that an error in side friction capability of less than 0.15 leads to a 10 percent error in the estimated safe speed of a curve. Changes in precipitation, tire condition, and road roughness can easily lead to a significant friction discrepancy. An infrastructure-based system may give good information about the weather or even the precipitation present on a particular roadway segment, but the infrastructure certainly does not know the current tire condition. Conversely, a friction-measuring system contained within a vehicle can probably account for the condition of the tires, but it would be completely unaware of ice patches that lie ahead. Even so, measuring the tires' ability to avoid hydroplaning may be difficult until a puddle of water presents the opportunity...too late for safety. Perhaps the countermeasure system should be combined with a vehicle maintenance program, reminding the owner to rotate the tires or check their tread depth at the proper time. To be sure, as development of a longitudinal countermeasure system continues, getting a reliable, accurate friction measurement will be an important issue.

The key assumption in the sensitivity analysis in this section is that a 10 percent error in curve entry speed is tolerable. If the excess speed is small, the difference will likely result in a slightly increased lateral force. For example, if a vehicle plans to enter a 1000-ft-radius curve with a 4 percent superelevation at 88 fps but has a 10 percent speed error, the side friction factor will be 0.25 rather than the planned 0.20. This is within the capability of most non-icy surfaces and probably tolerable for the passengers. If the excess speed is too high, the driver will need to maneuver more carefully and perhaps increase the radius slightly (i.e., depart the lane). Should the driver panic because of an unexpectedly high side force or squealing tires and apply the brakes, control of the vehicle may be lost. Therefore, as with the lateral countermeasure systems, the question of stability ultimately becomes a matter of human factors. This analysis above is suitable for planning a countermeasure system, but more information on human drivers' practices is needed before final performance specifications can be written.

If a 10 percent error in curve entry speed is shown to cause instability in too many cases, the safety margin will have to be increased. Similarly, if the minimum achievable errors in parameter estimates combine to produce an error of more than 10 percent, the cushion will again have to be increased, by lowering the estimated safe speed of the curve. The drawback of this additional safety margin is the greater likelihood of false alarms, when the conservative countermeasure warns a driver who was well aware of the situation and was planning to slow down anyway.

Results of Task 3 technology testing and Task 4 modeling indicate that, overall, the technology exists for a longitudinal countermeasure that can provide a reliable and timely warning when approaching a curve at excessive speed. Certain road departures related to excessive speed in a curve should be preventable with this type of countermeasure. For instance, 23 percent of the curve-related excessive speed crashes in the Task 1 database were caused by the driver being unaware of the upcoming curve. Our analyses indicate a longitudinal countermeasure should prove extremely effective in this type of situation.

Human factors issues will play a dominant role in determining the ultimate effectiveness of a longitudinal countermeasure. For example, 59 percent of the speed-related curve departures in the Task 1 clinical database involved drivers impaired by alcohol. The likely response of these drivers to a longitudinal warning system needs to be further investigated before the final performance specification can be written. Protecting impaired drivers may require countermeasures that adapt to the characteristics of the driver or provide active control intervention. Also, even alert drivers have differences in their skills and desires for curve handling. This, too, would require that the system somehow adapt to the individual.

8.0 Performance Specifications to Meet Functional Goals

This section presents preliminary performance specifications for in-vehicle countermeasure systems to assist in avoiding Run-Off-Road (ROR) crashes. These preliminary performance specifications were generated to address the functional goals for ROR countermeasure systems developed in Task 2 of this program. The overall intent of these preliminary performance specifications is to provide engineering guidance for the design of future ROR countermeasure systems.

The preliminary performance specifications are organized according to the eleven functional goals listed in Table 8-l. A twelfth section, on overall system performance, presents a few specifications that are not tied to a functional goal. Under each functional goal, the preliminary performance specifications generally applicable to all potential ROR situations are listed first. General specifications are numbered as [G-]. They are followed by specifications unique to lateral and longitudinal systems as necessary. Specifications pertaining to lateral countermeasure systems are numbered as [T-], and specifications associated with longitudinal countermeasure systems are numbered as [N-]. Commentary on the intent or possible extensions is included with the specifications.

Table 8-1
Functional Goals for a Run-Off-Road Countermeasure System

1. Monitor the Vehicle Dynamic Status
2. Determine Geometric Characteristics of the Upcoming Roadway Segment
3. Determine Vehicle Position and Orientation Relative to the Roadway
4. Determine Driver Intention
5. Detect Degraded Roadway Conditions
6. Process Data to Determine the Acceptable Speed for the Approaching Roadway Segment
7. Detect the Potential for Roadway Departure
8. Present a Phased Alarm to the Driver
9. Determine the Driver State
10. Modulate the Driver Control Input
11. Maintain or Regain a Safe Vehicle Attitude

To be as comprehensive as possible, the performance specifications must be generalized so that they are independent of the properties of a particular algorithm. Although this desirable objective was met whenever possible, it can accomplished only in a limited number of cases (e.g., maximum lateral or longitudinal acceleration for the which the vehicle is physically capable). The inability to generalize at this time is partly due to the small number of algorithms that were examined during this project. The differences of the two lateral systems forward-looking and downward looking, though, did help shed light on possible ways to generalize specifications.

These preliminary performance specifications were developed by the methodology and analysis discussed in the previous sections of the present Task 4 report. The analysis included use of the computer simulation program RORSIM developed for this project. RORSIM was used to simulate operation of two lateral countermeasure systems under diverse circumstances. The simulations are presented in Section 6 of this report. The performance and shortcomings of the two systems in the simulations suggested several of the following specifications. Some of the specifications grew out of the RORSIM comparison of the two electronic systems with shoulder rumble strips. The specifications related to longitudinal systems were derived from analysis of the relevant equations. As discussed in Section 7, they are based in part on the premise that a 10 percent error in curve entry speed will not degrade vehicle control ability or diminish passenger comfort. Other specifications were derived from the engineering analysis conducted as part of Task 3 of this project. Where possible, particular values have been inserted in the specifications. These numbers result from the research reported in the previous sections of this report, previous task reports of this project, other relevant references, or other engineering analysis. In places where a number is required but no research data is available to suggest a value, TBD (to be determined) has been inserted in place of a number.

The analysis conducted for this task primarily involved vehicle kinematics and dynamics. Driver behavior was investigated to a smaller extent. The project team has attempted to make the list of preliminary performance specifications as complete as possible, including specifications from disciplines other than dynamics. However, we must stress that experts in the relevant fields should be consulted to determine the necessity and proprietary of the specifications. Technical aspects of the specifications should be subjected to verification through further simulation and field testing. Further refinement and expansion of these specifications will take place in Phases II and III of this program. In addition, specifications from the following list that are demonstrated through further investigation not to be necessary for effective countermeasure performance will be eliminated. Above all, the specifications in this section are, as the title of the task suggests, preliminary.

8.1 Monitor the Vehicle Dynamic Status

Nearly the entire vehicle state vector may be required for some countermeasure systems. Conversely, other systems, such as CMU's implementation of the TLC algorithm, do not require any vehicle dynamic state information. The two specifications listed here for lateral systems apply to the implementation of the TTD system that was investigated in this program. This system computes the time it will take the vehicle to diverge from the ideal trajectory determined by the countermeasure. To compute this time accurately, the system needs to know both the vehicle's forward speed, and the vehicle's yaw rate.

While exact values for the above specifications have yet to be determined, it appears from the project team's experiments that existing velocity and yaw rate sensors should be sufficient to provide this information.

[T-1] The system shall measure the vehicle's forward speed to an accuracy of TBD ft/s.

[T-2] The system shall determine the vehicle's yaw rate to an accuracy of TBD rad/s.

The important quantity in the vehicle dynamic state for longitudinal systems is the speed. An error in the speed's measurement would propagate directly through the longitudinal countermeasure algorithm and continue through the evolving event. The sensitivity analysis in Section 7.3.5 indicates that errors in vehicle speed of greater than 4 fps will lead to unacceptable errors in curve entry speed.

[N-l] The system shall measure the vehicle's speed to an accuracy of 4 fps.

To minimize false alarms when the vehicle is maneuvering in unstructured environments (e.g., parking lots) or executing some other non-threatening maneuver (e.g. pulling to the side of the road) a roadway departure countermeasure should operate only when the vehicle is moving faster than TBD fps.

[G-l] The roadway departure countermeasure shall operate when the vehicle's speed is above TBD fps. Below this speed, warning and control intervention by the countermeasure shall be suppressed.

8.2 Determine Geometric Characteristics of the Upcoming Roadway Segment

Several specifications relating to the geometry of the upcoming road segment are crucial for effective countermeasure operation. First, the countermeasure should be able to determine whether the vehicle is on a road.

[G-2] The system shall be capable of detecting when the vehicle is traveling on a roadway, as opposed to a parking lot or other unstructured environment.

[G-3] When traveling in an unstructured environment, the countermeasure shall suppress all road departure warnings and control intervention, to avoid nuisance alarms.

When the vehicle is on a road, both the longitudinal and the lateral countermeasures must be capable of handling arbitrary road types, including those without lane markings, since degraded or missing lane markers are relatively common, particularly in rural environments.

[G-4] The countermeasure shall be capable of operating on the range of typical road types, including those without lane markings, and on those where the lane markings are worn or in some other way degraded.

A roadway departure countermeasure should be able to handle all curves of reasonable sharpness, to be applicable to highway and rural road situations.

[G- 5] The system shall be capable of performing its functions on curves with a radius of curvature as small as 200 ft. It shall disable warnings and control interventions when it determines that the road curvature is smaller than it can accommodate.

[G-6] The system shall accommodate changes in curvature of as much as TBD 1/ft per ft.

Changes in grade are a common occurrence, particularly on rural roads, which have the potential to provide difficulties for some countermeasure systems. For instance, when cresting a hill, the road ahead has the potential to leave the field of view of a countermeasure's sensor.

[G-7] The system shall accommodate changes in grade of as much as TBD percent per ft.

Both lateral and longitudinal countermeasures must be able to detect the presence of other lanes on the roadway, as well as cross streets and exit ramps. This capability is crucial for avoiding false alarms, and for correlating the vehicle's trajectory with the driver's intentions.

[G-S] The system shall be capable of detecting the presence of cross streets, exit ramps and additional travel lanes within a range of TBD feet ahead of the vehicle.

The width of the travel lane is an important parameter for a lateral countermeasure, since it is within this range that the vehicle must operate. The Task 4 analysis indicates that there is a direct correspondence between errors in the lane width estimate by the countermeasure and expected lane exceedence by the driver. The lane width estimate is particularly important on roads with little or no shoulder.

[T-3] The system may assume a minimum lane width of 8 ft at all times. However, when the system measures a wider lane, it shall use a width that is its 95-percent confidence limit of the actual lane width. When the measured lane width is greater than 14 ft, the system shall advise the driver of a possible malfunction.

[T-4] The system shall be capable of estimating the width of the travel lane to an accuracy of 0.5 ft.

For a system that protects against excessive speed through curve, both the curvature and the superelevation of the upcoming road segment are important. The valves in the next two specifications are both half of the "tolerable" errors calculated in Section 7 to allow for the inevitable error of errors.

[N-2] The system shall determine the curvature of the upcoming roadway segment to an accuracy of 10 percent of the actual curvature. The determination may be provided by a direct measurement, a roadside transponder, or a reliable database.

[N-3] The system shall determine the superelevation of the upcoming roadway segment to an accuracy of 0.03 ft/ft. The determination may be provided by a direct measurement, a roadside transponder, or a reliable database.

8.3 Determine Vehicle Position and Orientation Relative to the Roadway

In addition to detecting the geometry of the road ahead, a countermeasure will need an accurate and reliable estimate of the vehicle's position and orientation relative to the roadway. It should be able to make this estimate in the range of environmental conditions vehicles typically encounter. (Note that Specifications G-9 through G-l 1 apply *to* the system as a whole and are not limited to this one functional goal. They are especially pertinent to the second functional goal, determining the roadway characteristics. They are listed here because they apply to the sensors.

[G-9] The countermeasure shall be capable of operating in all reasonable environmental conditions. This shall include both day and night operation. It shall also include operation in rain, snow, sleet and fog. In the rare condition that environmental conditions are so severe as to significantly degrade countermeasure performance, the countermeasure shall recognize this, discontinue operation and report the situation to the driver.

Occasionally a countermeasure may experience brief periods during which an accurate estimation of the vehicle's position relative to the roadway may not be possible. These might occur when there is a short gap in the lane markings at an intersection, or when GPS lock is lost because a building occludes one or more satellites. A countermeasure needs to be able to handle these situations reasonably.

[G-10] The system shall function without interruption during brief periods when it cannot accurately estimate the position of the vehicle relative to the roadway. During these periods, the countermeasure should use previous estimates of roadway geometry and the vehicle's trajectory to extrapolate the current position of the vehicle relative to the roadway. The system must be capable of extrapolating for at least 25 ft or 0.5 s.

[G-11] If signal loss persists for a sufficient period to make accurate extrapolation impossible, the system shall non-intrusively inform the driver of the countermeasure's degraded performance status. The system availability due to signal loss or other malfunction shall not fall below TBD percent of the total time the vehicle is operating on roadways.

For a lateral countermeasure, there are potentially two important parameters relating the vehicle's position to the roadway. They are the vehicle's lateral position within its lane, and the lateral position of the lane center ahead of the vehicle. A particular lateral countermeasure may require estimating one or both of these parameters.

[T-4] The system shall measure the lateral position of the vehicle within the lane to an accuracy of 0.1 ft.

[T-5] The system shall be capable of detecting the lateral position of the lane center up to 2.0 ahead of the vehicle's current location, with an accuracy of better than 1.0 ft.

A longitudinal countermeasure system must measure the distance from the vehicle to the curve entry point. Furthermore, the curve must be noticed in time for the system to act and the driver to respond. The 2.5 s reaction time allowance was selected because it will accommodate 95 percent of drivers as shown by Figure 5-5.

[N-4] The system shall measure the distance from the vehicle to a restricted-speed road feature (such as a curve entry) to an accuracy of 20 ft.

[N-5] The system shall detect and identify restricted-speed road features when the distance between the vehicle and the feature is not less than

$$d = \frac{V^2 - V_c^2}{2a} + t_r V \qquad (8\text{-}1)$$

where

V = the current vehicle speed
V_c = the planned curve entry speed
a = the planned deceleration rate
t_r = the allowed braking reaction time.

The reaction time in the equation shall be taken to be not less than 2.5 s for the driver plus any time required by the system itself.

The anticipated deceleration shall be taken to have a magnitude not greater than 6 ft/s^2.

The restricted speed shall be taken to be the minimum conceivable a priori speed:

50 fps (35 mph) on freeways and other divided highways
15 fps (10 mph) on all other rural highways and roads.

8.4 Determine Driver Intention

The analysis indicates that to be effective, the lateral system will need to be quite sensitive to lane excursions. Because of this sensitivity, intentional lane excursions, whether due to lane change maneuvers, evasive maneuvers or even simply pulling off to the side of the road, will need to be recognized as intentional to minimize false alarms. This requirement could potentially be accomplished using techniques as simple as monitoring the vehicle's turn signals for indications of a lane change, or as sophisticated as learning to distinguish between intentional and unintentional control inputs for a particular driver. The level of reliability for intentional maneuver detection methods necessary to minimize false alarms to an acceptable level has yet to be determined, and will likely vary substantially from one driver to another.

[T-6] The system shall not prohibit a driver from making safe lane changes, driving on the shoulder to avoid obstacles in the lane of travel, or stopping beside the road for a vehicle or passenger emergency.

[T-9] The system shall permit two tires on one side of a vehicle to depart the lane by as much as 1 ft on a long, continuous curve, provided that the rate of approach to the edge line is less than 0.25 ft / s.

A skilled, alert, aggressive driver would enter a curve well above the posted speed and to the outside of the lane, planning to follow a path that maximizes the effective radius of the curve. However, an inattentive driver who is unaware of the very presence of the curve might approach it with the same speed and trajectory as the aggressive driver. A system of modest design would not accommodate differences in driver skill at all. A slightly more sophisticated system would permit the driver to override it on a curve-by-curve basis. A truly advanced system would sense the driver's intention to follow a near-optimal trajectory. Therefore, one of the following performance specifications will apply:

[N-6a] The system shall base its calculations of the maximum safe speed on a maximum curvature that is TBD percent higher than the maximum geometric curvature of the road segment. This requirement accounts for the typical driver's pattern of negotiating curves with a non-uniform curvature.

[N-6b] The system, after alerting the driver to the presence of the curve, shall permit the driver to indicate, through a specific action, an awareness of the curve. When the driver gives such an indication, the system shall base its calculation of the maximum safe speed on the maximum geometric curvature of the road segment.

[N-6c] The maximum safe speed calculation shall be based on the expected trajectory of the current driver through the upcoming curve. The system shall monitor and record the driver's practice of approaching and negotiating curves on each curve and develop a pattern of the driver's practice. As the vehicle approaches a curve, the system shall measure the vehicle's lateral position in the

road and all other parameters necessary for comparison with the established practice to predict the driver's intended trajectory through the curve. The system shall determine when the driver changes and shall apply the principles of Specification [N-6b] or [N-6a] until a pattern has been established.

8.5 Detect Degraded Roadway Conditions

In a construction zone, obstacles (i.e., barrels) are close to the travel lane. The obstacles may confuse a vision-based system, at a time when running off the road has particularly harsh consequences. The pavement may drop off suddenly outside the lane, or workers may be standing next to the traffic. Similarly, under narrow bridge abutments or in tunnels, the cost of a lane departure can be quite high. Therefore, if a system cannot meet the following specification with certainty, it must disarm itself and inform the driver that it has done so.

[G-12] The system shall be capable of detecting when the lane is restricted by construction barrels, bridge abutments, or other obstacles near the road. When it detects such restrictions, it shall adjust its warning thresholds so that the probability of a missed warning in an imminent lane departure drops to not more than TBD percent, while holding the probability of a spurious warning to TBD percent. If necessary, the system shall direct the driver to slow the vehicle so that this specification can be met, though the commanded speed must not be below the applicable minimum legal speed limit.

In addition to road geometry, the safe speed in a curve depends strongly on the condition of the roadway, particularly the friction. Friction affects both the vehicle's ability to negotiate a curve and its ability to slow down before a segment with restricted speed. Other roadway conditions, such as obstacles in the road, would also affect the maximum safe speed, but they are not addressed in these specifications. The quality of the friction measurement is stipulated below, but the measurement could come from one or more sources. If, for example, the friction is inferred from the dynamic state of the vehicle, then many dynamic variables would be needed. For the purpose of this list, the friction measurement is considered a subsystem, and specifications for its internal operation are not explicitly listed here.

[G-13] The system shall determine the available side friction coefficient in the upcoming roadway segment to an accuracy of 0.05. The system shall be capable of identifying isolated regions of reduced friction, such as ice patches, as small as TBD ft^2.

[N-7] The system shall determine the available longitudinal friction coefficient in the roadway over a distance ahead of the vehicle given in specification [N-5].

A lateral system will have to be installed and adapted to the vehicle itself to account for the maneuvering capability of the vehicle.

8.6 Process Data to Determine the Acceptable Speed for the Approaching Roadway Segment

The safe speed for a roadway segment may be calculated entirely within the vehicle (as in the case of a curve), or it may be based in part or in whole on the infrastructure (for example, in a school zone). When the system calculates the maximum safe speed, Specification [N-8a] applies; when it acquires the safe speed from the infrastructure, Specification [N-8b] applies.

[N-8a] The maximum acceptable speed for the approaching segment shall be determined from the equation,

$$V = \sqrt{Rg\frac{e+f}{1-ef}} \tag{8-2}$$

where

R = the planned minimum curvature of the vehicle's path through the road segment
g = the acceleration due to gravity
f = the planned side friction factor
e = the estimated superelevation of the road segment.

The values for R, e, and f may be measured directly by the vehicle, retrieved from a reliable database, or acquired from the infrastructure, subject to the accuracy constraints imposed by other specifications.

[N-8b] The vehicle's system shall acquire the maximum safe speed for the approaching roadway segment from the infrastructure-based component of the system.

[N-9] After determining the nominal maximum safe speed for a curve, the vehicle's system shall adjust the maximum safe speed according to vehicle-specific parameters such as rollover susceptibility, roll stiffness, and mass distribution.

[N-10] The combined errors in all above measurements shall be such that the system has a 95 percent confidence that the actual maximum safe speed of the segment is equal to or less than the estimated maximum safe speed.

The acceptable speed of an approaching roadway segment affects the lateral stability of a vehicle in that a driver may lose directional control when driving too fast on a slippery surface. If a primarily lateral (steering) countermeasure system has detected that the roadway conditions are degraded, it may determine a maximum safe speed and warn a driver who is exceeding the speed.

8.7 Detect the Potential for Roadway Departure

The goal of the system, of course, is to reduce the number of crashes as much as possible while keeping the false alarm rate as low as possible. The fields of statistics and signal detection have mathematical formalisms for doing this.

[G-14] Algorithm and parameter selection shall maximize crash hazard detection and minimize false or nuisance alarms.

While assessing the potential for a roadway departure, the system should not anticipate an acceleration (longitudinal or lateral) that will exceed the capability of the vehicle or cause undue discomfort to the driver or passengers.

[G-15] A warning shall be issued when a projected recovery maneuver will require more than 6.0 ft/s^2 longitudinal acceleration or 4.0 ft/s^2 lateral acceleration, or 50 percent of the current estimated acceleration capability of the vehicle, whichever is less. In systems providing for intervention, the maneuver executed by the system shall have a peak acceleration of not more than 20 ft/s^2 longitudinal and 15 ft/s ^{2} lateral, or 90 percent of the estimated acceleration capability of the vehicle, whichever is less.

The lateral system, by some algorithm, will project whether the current trajectory leads the vehicle off the roadway. When a serious departure is expected, the system must assess the urgency of the situation, either in terms of the time remaining until a crash, the speed of the steering correction required to avoid the crash, or another measure.

[T-S] The system shall quantify the danger of lane departure and trigger a response if the danger exceeds some threshold. The danger may be measured in terms of time remaining until departure, the magnitude of the steering correction maneuver required to avoid the crash, or some other measure.

[T-9] The decision algorithm must consider the expected driver reaction time in determining when to trigger an alarm. The assumed reaction time in a lateral countermeasure system shall be no less than 1.5 s, including the time required by the countermeasure, the driver, and the vehicle.

A longitudinal countermeasure must decide whether a roadway departure due to excessive speed is imminent, based on the data collected in the previous functional goals characterizing the state of the vehicle and roadway.

The system shall compare the vehicle's current speed with the maximum speed that will allow the vehicle to decelerate to a safe speed before reaching the curve or other restricted-speed roadway segment. This comparison shall take into consideration both the distance to the upcoming road segment and the maximum safe speed for traversing it.

[N-12] The measurement acquisition, processing, and decision making functions shall be completed so that the phased alarm sequence, if necessary, can begin in time to give the driver adequate warning. The warning distance shall be as determined in specification [N-15].

8.8 Present a Phased Alarm to the Driver

The concept of a phased alarm is that a driver will first be alerted, or merely reminded, that a hazard lies ahead, even before an emergency begins to develop. If the driver does not respond to an alert, a more urgent warning will be issued. The warning might communicate to the driver through visual (e.g., a light), auditory (e.g., a buzzer), or tactile (e.g., a shaking handwheel). The communication should convey an appropriate sense of urgency. As far as is possible, the warning should be quickly interpretable, even by drivers not familiar with the system. General thresholds for initiating a warning were given under the seventh functional goal. Even if the warning cannot be issued in time to prevent a crash, the system should warn the driver in hopes of reducing the severity of the inevitable crash.

[G-16] The system shall provide one or more signals to alert the driver to the crash hazard. To the extent feasible, this signal onset shall be such that the driver has sufficient time to successfully execute an appropriate crash avoidance maneuver.

[G-17] The system may signal the driver through visual, audible or tactile means. Due to the primacy of visual attention in highway safety, the visual demand on **the driver away from the driving scene shall he minimized.**

[G-18] To the extent possible, the signals shall convey the urgency of the danger. Urgency may be conveyed through choice of modality (e.g. visual for low urgency, audible for higher urgency), or through the characteristics of the signal within a particular modality (e.g. louder or higher pitch audible tones for higher urgency). If sufficient time is available, several signals of increasing urgency may be provided to the driver.

[G-19] The signals shall be easily interpretable, and distinct enough so as not to be confused with other in-cab signals. If graded-urgency signals are provided, the signal when a crash is imminent shall be distinct from other warning signals.

The following functional goal is complex, involving design decisions on many signal attributes such as intensity (e.g., luminance, contrast, polarity, hue saturation), duration (e.g., rise time, on-off duty cycle, presentation rate), tonality (pitch, volume, timbre), etc. Also, the stimuli in the cab may come from outside the cab, e.g., veiling glare on a visual display from sunlight coming in through the cab windows. Finally, in-cab masking stimuli may be situation-specific, e.g., only if the radio is on, need it be turned down.

[G-20] The signals shall be designed such that they are not masked by other signals or stimuli normally present in the cab. This may require suppression of other in-cab distractions (e.g. radio) during countermeasure signaling.

[G-21] The signals shall not be so intense or complex as to overload the driver's sensing and processing capabilities, or startle the driver into an inappropriate response.

[G-22] The countermeasure signal intensity may be adjustable by the driver. However if such an adjustment is provided, there shall be minimum signal intensity, below which it cannot be adjusted. This minimum intensity level will depend on the modality and other characteristics of the signal, but will be no lower than the intensity detectable by 95 percent of the population under typical in-cab conditions. Feedback on the results of driver adjustments shall be provided to the driver during the adjustment process.

Where possible the countermeasure system should help the driver know how to respond to a warning. For example, the system might provide a directional signal to tell the driver which way to steer. An directional audible signal might be a tone emanating from the direction of departure. A directional haptic signal might be a momentary torque to the steering wheel in the direction which will return the vehicle to the travel lane.

[G-23] The signals should in some way indicate the appropriate driver response, as long as this information can be conveyed without reducing the signals' interpretability or increasing the driver's confusion.

To account for driver-to-driver variations in such parameters as reaction time or aggressiveness, the system's thresholds might be adjustable by the driver. Where the driver can adjust the sensitivity, there must be feedback to the driver as to where, between minimum and maximum limits, the threshold is set. The adjustment limits would be based on the known handling capabilities of the vehicle and established ranges of human reaction time. A system might have pre-determined settings for each of several drivers (probably tied in with the seat adjustment for different family members). A more sophisticated system might somehow sense the driver's preferences through driving style, as suggested for curve negotiation in specifications [N-6a] through [N-6c].

[G-24] Detailed system design features shall incorporate human factors design guidelines and principles as contained in COMSIS (1993), MIL-STD-1472D, and other human factors documents as appropriate.

[G-25] User orientation to the system should be provided via documentation, video, demonstration, or training.

8.9 Determine the Driver State

A simple, yet potentially effective countermeasure system would not need to determine the driver state at all; it would simply present the driver with an alarm at the point dictated by the vehicle state and the geometry. A more sophisticated system might monitor the driver's condition for at least three purposes: (1) A system might sense the driver's vitality and adjust the reaction time allowance accordingly. (2) A system with partial capability to control the vehicle would intervene to slow the vehicle when the driver failed to respond to all'of the warnings. (3) A system with yet more sophisticated control capabilities would safely stop the vehicle when it sensed that the driver was not responding at all. While this program has not focused on methods for monitoring the driver's state, there are several performance specifications for roadway departure countermeasures relating to this function.

[G-26] When feasible, a countermeasure shall monitor the driver's state for signs of fatigue, inattention, or incapacitation.

[G-27] The monitoring of driver state **shall be performed in a non-intrusive manner, so as not to interfere with the driver's comfort or ability to perceive the environment and control the vehicle.**

The system shall compare the vehicle's current speed with the maximum speed that will allow the vehicle to decelerate to a safe speed before reaching the curve or other restricted-speed roadway segment. This comparison shall take into consideration both the distance to the upcoming road segment and the maximum safe speed for traversing it.

[G-28] If the countermeasure determines the driver's state to be degraded beyond an acceptable level, it shall alert the driver with a signal subject to specifications G-16 through G-25.

8.10 Modulate the Driver Control Input

If the driver does not respond to warning signals, modulation of the driver's control input may be required. If the driver does not heed the lane departure warning, the system may decide to augment the force the driver is applying to the steering wheel. If the driver does not heed the warnings about speed, the system may decide to slow the vehicle. As with cruise control, however, the driver must have an instant, intuitive means of disengaging the countermeasure system. When the driver is applying the brakes to slow for a curve, the system may apply more braking if warranted by the thresholds under functional goal seven, but it must fully return control to the driver when the driver increases pedal force in response to active braking. Some systems may not have intervention capability.

[G-29] When sufficient time is available, modulation of driver control input shah be delayed for a long enough time after the onset of the warning signal(s) to give an alert driver time to undertake corrective actions manually.

[G-30] If the driver does not respond to the warning signals, and the danger of roadway departure continues to increase, the countermeasure may modulate the driver's control input to facilitate crash avoidance. This modulation may take the form of steering, brake, throttle or gear shift input.

[G-31] The modulation of control inputs shall be of sufficient intensity and duration to begin the corrective maneuver, but not so intense or extended in duration that they result in control instability.

[T-10] Torque applied to the steering wheel to begin correcting the vehicle's trajectory shall be no more than TBD in amplitude, and no more than 0.5 s in duration.

[T-11] The system must return complete steering control to the driver when the driver puts a torque of TBD in-lb on the handwheel for more than 0.2 s. After the driver has overridden the intervention, the system must not again attempt to control the vehicle for at least 5 s.

[N-13] The system must return complete speed control to the driver when the driver puts a force on the brake pedal of more than TBD lb for more than 0.2 s. After the driver has overridden the intervention, the system must not again attempt to control the vehicle for at least 5 s.

[N-14] The system must ensure that the deceleration applied by the vehicle does not impair the driver's ability to steer the vehicle. Active braking intervention must be applied only in vehicles equipped with antilock braking systems (ABS).

8.11 Maintain or Regain a Safe Vehicle Attitude

In the event of continued lack of response from the driver to the phased warnings, an extremely sophisticated system might take momentary control of the vehicle, slow its speed, and steer it safely to the side of the road. Note that this functionality would require a level of reliability on the part of the countermeasure that is not likely to be available in the foreseeable future.

[G-22] If the driver fails to respond to both warning signals and control input modulation, the countermeasure may assume momentary control of the vehicle to slow it down and steer safely to the side of the road. This function should be invoked only by countermeasures with extremely reliable sensing and processing capabilities, including the ability to detect obstacles in the potential path of the vehicle.

8.12 Overall System Performance

The previous specifications have addressed the form and function of the individual components in a roadway departure countermeasure. However the overall performance of such a system is ultimately determined by how well it keeps the vehicle safely on the road. One potential method for quantifying the minimum performance requirements for such a system is to measure its ability to prevent a suite of potential run-off-road crashes. These tests could be performed using a dynamic simulation, or preferably using controlled live tests on a test track. In this approach, the countermeasure would be tested in every situation in the suite, covering a range of speeds, weather conditions, driver styles and other factors to ensure reliable performance. In each situation, the maximum lane violation will be recorded. The distribution of the violations of the proposed system must be, at all lane deviation levels, better than those in the table below. The distribution of the lane exceedances must not be less than those in Table 8-2 (which is TBD).

When performing the test suite, the system shall not prematurely warn the driver in more than 10 percent of the cases. Furthermore, in a test suite of “normal” driving scenarios, the system shall not issue a warning at a rate equivalent to more than once in ten hours of driving.

Table S-2
Preliminary Standard for Evaluating Run-Off-Road Countermeasure System by Simulating Lane Departure

Maximum Lane Violation	**Cumulative fraction of cases not exceeding this lane violation**
0.0 ft (i.e., the vehicle does not depart its lane)	70%
0.5 ft	80 %
1.0ft	90 %
1.5 ft	95 %
2.0 ft	98 %

While some type of individual countermeasure testing will almost certainly be necessary to ensure proper performance, the form and content of practical tests for this purpose remains to be determined.

The following general specifications also apply to the overall function of every collision avoidance system:

[G-33] The system shall incorporate fail-safe design principles to the extent possible. When the system determines that it cannot operate properly (due to, for example, low-quality incoming signals or component failure), it shall non-intrusively advise the driver of the malfunction and refrain from issuing warnings or control interventions until the malfunction has ended.

[G-34] The system shall be activated upon application of power to the vehicle. It shall operate continuously when the vehicle is in operation, except as provided in specifications pertaining to low vehicle speed, corrupted sensor signal, or a system malfunction .

9.0 Summary and Conclusions

A sophisticated analytical tool, RORSIM, was developed in this task. This time-domain computer simulation code was used extensively to explore the viability of run-off-road countermeasure systems and to develop preliminary performance specifications associated with the functional goals for these systems.

Three proposed countermeasure systems were studied analytically and through simulation modeling. All were shown to be potentially quite effective in reducing the rate of run-off-road crashes on highways. Two of the systems are lateral countermeasures. They provide warnings to prevent crashes where an inattentive or incapacitated driver drifts off the road. In extreme situations, they may provide momentary steering control. The third system is longitudinal in nature. It provides warnings and possibly momentary speed control to prevent crashes caused by excessive speed, particularly on curves.

9.1 Capabilities of RORSIM

The project team has developed, tested, and used a computerized mathematical model to estimate the effectiveness of run-off-road crash countermeasure systems. The model accounts for pertinent input variables, including the dynamic behavior of the vehicle, the reaction time of the driver, the properties of the sensors. Each sensor and each decision-making algorithm is implemented as a distinct module of program code, so countermeasure systems can be added or modified with little effect on the program as a whole.

RORSIM has many more features and capabilities than were exercised as part of this task. Most notably, many kinds of noise and degradation can be applied to the sensor outputs. Also, more complicated roadway designs and surface conditions can be modeled with RORSIM. Because of the flexibility of VDANL, the vehicle model on which RORSlM is based, vehicles other than the Ford Taurus used for this project can be easily modeled.

The current driver model in RORSIM is that provided by VDANL; its usefulness for evaluating the interaction of a driver with a countermeasure system is limited. As more accurate and detailed data on driver performance with and without countermeasure systems are generated, the RORSIM driver model should be refined and verified. This will improve the predictive capability of an already effective analytical tool for collision avoidance research.

9.2 Potential of Lateral Countermeasure Systems to Meet the Functional Goals

Analytical studies were performed to compare the performance of two proposed lateral countermeasure systems to shoulder rumble strips, a passive countermeasure system that has been proven to be quite effective in actual use.

Shoulder rumble strips (dubbed the Sonic Nap Alert Pattern or SNAP by the Pennsylvania Turnpike Commission) contributed to a 70-percent reduction in run-off-road crashes during a test period. These strips, which are cut into the shoulder a few inches outside the edge line, provide an audible and compelling notice to the driver that a lane departure has occurred. Electronic countermeasures, with the potential to warn a driver before a lane departure occurs, offer yet greater ability to help the driver with the lane-keeping task. This is especially important on rural highways. On a two-lane road with little or no shoulder and a truck in the oncoming lane, the consequences of even a small lane departure are particularly adverse.

Drivers responding to SNAP-like warnings kept the vehicle's tires within 2 to 2-l/2 ft of the edge of a l2ft-wide lane in 70 percent of the cases as simulated by RORSIM in the parameter studies. Drivers assisted by one of the two proposed countermeasure systems kept the tires within 1/2 ft of the lane edge in 70 percent of the same cases, and within 2-l/2 ft of the lane in all of the cases. This excellent crash prevention effectiveness was achieved with the warning thresholds set low enough to avoid false alarms during non-emergency situations, as determined by the RORSIM driver model and a human driver.

Our analyses in this task have shown roughly similar effectiveness of the two proposed lateral countermeasure systems. The forward-looking system is less affected by sudden changes in road curvature, and it calculates a desired steering angle, which would be useful in steering intervention. The downward-looking system had slightly superior performance in the parameter studies. Because of its much shorter look-ahead distance, the downward-looking system would be less affected by fog.

The current critical technical issues for RORSlM are ensuring that it accurately models key components of the crash sequence. Tasks 2 and 3 of this project have generated data that could be analyzed further and incorporated in RORSIM to more accurately model human driving behavior in normal and emergency conditions. Also, some of the dynamic analysis of actual crashes conducted in Task 2 could be extended to provide more realistic crash scenarios for RORSIM. An expanded test suite of potential crash situations, selected to parallel the blend of scenarios in the clinical database, would be indispensable in forming more quantitative effectiveness estimates of proposed countermeasure systems.

9.3 Potential of Longitudinal Countermeasure Systems to Meet Functional Goals

Because excessive speed in a curve is a major cause (32 percent) of run-off-road crashes, the need for improved driver awareness of upcoming curves is significant. Since 42 percent of the run-off-road fatalities occur in curves, the potential benefits of an effective countermeasure system are significant. Curve-warning countermeasure systems are generally less complex than the two lateral countermeasure systems studied. The technology studies in Task 3 and the analysis in Task 4 showed that building a curve warning system with available components is quite feasible.

The accuracy with which a longitudinal countermeasure system can determine the maximum safe speed for a curve depends strongly on the accuracy with which the curve radius and maximum available side friction force can be determined. Since the roadway geometry is fixed, the determination of the radius of an upcoming curve is relatively straightforward (e.g., using digital maps and GPS). However, the determination of maximum available side force is not straightforward, depending on several factors, including the road surface conditions, the tire conditions, and the angle of attack of the tires. Research effort should be directed at detecting and measuring slippery areas of road surfaces and communicating this information to the countermeasure system and ultimately to the driver. Countermeasure systems could be designed with safety margins to accommodate uncertainties in friction factor, but the frequency of false alarms generally will increase with increasing safety margins, which, in turn, would reduce drivers' acceptance of the system. Fortunately, if other factors are well controlled (and our analysis has shown that they can be) the safe speed can be reasonably well estimated in most conditions less severe than patchy ice. Because of the number and severity of speed-related run-off-road crashes in curves, a countermeasure system built on available technology could prevent a number of injuries and fatalities.

As with the lateral countermeasure systems, human factors, particularly driver skill, are an important consideration. The ability of a driver to steer smoothly through a curve and, when necessary, to avoid panic directly affects the ability of the vehicle to stay in its lane.

Active intervention in control of the vehicle's speed is relatively straightforward. The system merely needs to apply an appropriate force to the brake pedal. Complete control is restored to the driver when the pedal is released. The only caveat is that the braking tire force caused by the countermeasure system must not seriously degrade the lateral (steering) tire forces being used by the driver.

The analysis of the project team has shown that excessive speed, particularly in curves, is a factor to a significant number of run-off-road crashes and that an effective countermeasure system can be built.

9.4 Preliminary Performance Specifications

Viable performance specifications have been developed to address each of the broad functional goals developed in Task 2. The research in Tasks 3 and 4 of this first phase have helped in the formulation of the performance specifications, Through the modeling effort in the present task (Task 4), quantitative values have been developed for many, though not all, of the preliminary specifications.

An issue in developing performance specifications is to define the performance requirements without describing a particular system. The specifications should not dictate that a certain quantity must be measured when yet-to-be-developed system might meet the overall objective without directly measuring that quantity. Also, sensor or display details should not be mandated when their objectives could be met with different technologies. The specifications in this report are as technology-independent as possible, and they contain commentary to clarify the intention of the specifications.

Further work remains for Phases II and III of this program to refine, quantify, and validate the preliminary performance specifications developed in Phase I.

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